AMC PAMPHLET **AMCP 706-160**

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RESEARCH AND DEVELOPMENT OF MATERIEL

ENGINEERING DESIGN HANDBOOK

ELEMENTS OF TERMINAL BALLISTICS

PART ONE, INTRODUCTION, KILL MECHANISMS AND VULNERABILITY (U)

PART TWO, COLLECTION AND ANALYSIS OF DATA CONCERNING TARGETS (U)

See inside back cover for information on previous publications.

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PREFACE

Introduction, Kill Mechanisms, and Vulnerability, forming PART ONE of Elements of Terminal Ballistics, contains Chapters 1 through 4. Chapter 1 provides a brief history of terminal ballistics and a summary of current areas of interest in Terminal Ballistics.

Chapter 2 describes the various kill mechanisms, that is, the mechanisms for obtaining terminal ballistic effects. Chapter 3 covers target vulnerability for targets consisting of personnel, ground vehicles, aircraft, and surface and underground structures. Chapter 4 covers the collection and analysis of data concerning kill mechanisms.

A glossary and an index are included as part of this handbook.

The other handbooks which, together with this volume, comprise Elements of Terminal Ballistics are:

AMCP 706–161 (S)	PART TWO, Collection and Analysis of Data Concerning Targets (U)
AMCP 706–162 (S–RD)	PART THREE, Application to Missile and Space Targets (U)

Chapter 1 (U)

INTRODUCTION

Section I—Brief History of Terminal Ballistics

1-1. PRE NINETEENTH CENTURY

It can be speculated that man has always had a deep interest in increasing the effectiveness of the weapons he employed in his battle for survival. It was not until the time of Galileo and Newton, however, that scientific principles were developed and applied to problems associated with weapons and projectiles. The earliest problem to receive attention was that of determining the variation of range with the change of elevation angle, for a given gun, charge, and projectile. This may be considered the beginning of the general field of ballistics and, in particular, of what is now called "exterior ballistics". Science in the eighteenth century was occupied mainly with the development of mathematics, physics, and mechanics. The further application of these sciences to weapon problems was made in 1829 by the French engineer, J. V. Poncelet (1788-1867). Poncelet postulated a law of resistance for the penetration of projectiles into targets and conducted experiments to determine values for the two parameters involved. Poncelet's resistance law is still used today, as are experiments to determine the parameters for new target materials and projectile configurations. The work of Poncelet would appear to mark the beginning of what is now known as "terminal ballistics."

The general field of ballistics must be classified as an applied rather than a pure science. Developments in most applied sciences seem to be compressed into relatively short periods of time, wherein a particular external stimulus promotes rapid advances in the field. It is perhaps unfortunate, but true, that the applied science of ballistics is stimulated by national or international situations of war.

1-2. THE NINETEENTH CENTURY

1-2.1. General

During the nineteenth century, British military engineers were much concerned with the design and construction of ships and land fortifications to withstand penetration of solid projectiles. The first recorded instance in which a projectile was fired from a rifled gun at armor for land fortifications was in 1860, when an 80-pounder Armstrong gun fired wrought-iron, flat-headed shot, and a 40-pounder fired cast-iron shot, at two iron embrasures 8 inches and 10 inches thick fixed in masonry work at Shoeburyness (Ref. 1). Experiments with projectile effect on armor occurred rapidly after this. A selection of these experiments follows.

1-2.2. 1861—Armor Backed with Various Materials

Trials were conducted with wrought-iron armor backed with rigid materials, such as cast iron and granite, and backed with resilient materials, such as timber, cork, and rubber. The results indicated that the hard backing increased the resistance to penetration but led to cracking and to failure of fasteners.

1-2.3. 1862-1864—Simulated Ship Targets

Ship hulls were simulated, and trials were conducted with a 10½ inch gun firing 300-pound cylindrical shot at 1,320 ft/sec. There appears to have been a controversy at this time as to whether flat-nose or ogival-nose shot was more effective against armor. It was reasoned that the ogival shape would be deflected more readily by sloped armor.

1-2.4. 1865—Land Fortifications

Masonry targets 14 feet thick were fired on with 7-, 8-, 9.22-, and 10-inch guns at ranges

of 600 and 1,000 yards. Steel and cast-iron shot with hemispherical and elliptical (ogival) heads were used. The damage was assessed as follows:

1. 33 hits did serious damage.
2. 54 hits would have silenced return fire.
3. 86 hits destroyed the walls.

Other trials at this time brought out the excellent qualities of chilled cast iron for shot. This type of shot became known as Palliser shot, after Sir W. Palliser who suggested the idea. The trials also established the superiority of the ogival head over the blunt head.

1-2.5. 1871—Simulated Ship Targets with Spaced Armor

Two ship targets were simulated. The first was protected by a single plate built up to a thickness of 14 inches. The second target was protected by an 8-inch plate and a 6-inch plate separated by 9 inches of timber. The trials showed the superiority of the spaced armor. A series of trials was then conducted to determine the optimum spacing and filler material. It was concluded that a 5-inch space filled with cement was optimum. Apparently the spaced-armor technique was not widely used because no one knew quite how to employ it in the construction of fortifications. An interesting observation was made during these trials, however, as quoted directly from Ref. 1.

"It may be well to mention here a very remarkable result that was obtained in the course of the early trials with plate-upon-plate structures. When void spaces were left between the plates of these structures, it was found that the heads of the Palliser shells collapsed completely under the work they had to do in penetrating them, and, naturally, the effect produced upon the target was thereby very much reduced."

1-2.6. 1872—Ship Turret Tests

Trials were conducted at Portland using the turret of the HMS Glatton as the target and the 12-inch, 25-ton gun of the HMS Hotspur, at 200 yards range, as the weapon. The turret armor was 14 inches thick. Two Palliser shots were fired with 85-pound charges. The results reported (Ref. 3) were that ". . . there was some damage done inside the turret, but the goat, rabbit, and fowl emerged unharmed."

1-2.7. 1876—Early Use of a Massive Explosive Charge

An item of allied interest during this period was the use of a large quantity (52,000 pounds) of explosives to remove reefs in the East River in New York. There was apparently much speculation as to the effect the detonation of this quantity of explosives might have on structures in the surrounding area. It was reported that many people left their homes fearing possible collapse. Curiosity apparently overcame fear, however, because an estimated 250,000 people lined the river bank on the day of the blast. The charge was set off in September 1876, shattering millions of tons of rock. Eyewitnesses reported a rumbling or shaking of the ground, the rising of a great mass of water to a height of 20 to 40 feet, followed by an immense mass of smoke. There was no report of damage to any of the nearby structures.

1-3. THE TWENTIETH CENTURY THROUGH WORLD WAR II

During the early part of the twentieth century, military engineering interest was still centered in the field of penetration ballistics. However, during World War I several innovations were introduced which were the forerunners of new areas of interest. The airplane was introduced as a weapon carrier, and air-to-air combat led to interest in what is now called aircraft vulnerability. Chemical agents were introduced as damage mechanisms, ultimately leading to interest in personnel incapacitation by chemical and other means. Interest in damage to structures by blast, rather than penetration, arose from the possibility of aerial bombardment and from the realization that not all military targets could be fortified.

Pertinent developments in other fields provided facilities and instrumentation for much more exacting work in terminal ballistics. It was during this period that the major ballistics

research establishments were organized. In the United States, the Naval Ordnance Laboratory was formally established in 1929 and the Army Ballistic Research Laboratory was formally established in 1937. (Both of these had been functioning for a number of years prior to their formal activation under their present names.)

During World War II many new ordnance items were developed and introduced (Ref. 2). Some of these items were the proximity fuze, shaped charge ammunition, guided missile, aircraft rocket, flame thrower, and atomic bomb. Each of these new developments opened vast new areas for investigations in terminal ballistics.

1–4. POST WORLD WAR II THROUGH 1960

The largest area of terminal ballistic activity since World War II has been the atomic ~~and nuclear~~ weapons effects program. These operations were managed by the Armed Forces Special Weapons Project (AFSWP), and were participated in by all military services, as well as by numerous educational and industrial organizations. The new damage mechanisms of blast, and thermal and nuclear radiation have received a great amount of theoretical and experimental attention.

Second only to the nuclear weapons effects program has been the aircraft vulnerability program. For example, the development of the guided missile, capable of carrying various kinds of warheads, led to a terminal ballistic program concerned with the means of determining aircraft and missile vulnerability. This program has also been actively involved with such studies as the effects of explosive charges, delay fuzes, incendiaries, and high explosive loading in projectiles.

The introduction of the shaped charge has led to extensive analysis and testing of the shaped charge versus armor plate. In addition, the explosive launching of fragments has revived interest in the field of penetration ballistics.

The launching of earth satellites and the development of the ICBM have caused much interest and speculation in the possibility of new damage mechanisms. The investigation of these mechanisms is presently somewhat limited because facilities for controlled experimentation have not yet been perfected.

Section II—Current Programs in Terminal Ballistics

1–5. GENERAL

Virtually every world power is currently active in some aspect of the field of terminal ballistics. In the United States all of the military services have active programs, which taken together involve dozens of laboratories, research institutions, and industrial contractors. No attempt will be made in the following paragraphs to credit individual programs to the proper investigating or sponsoring agency. Rather, a summary of current areas of activity (Ref. 3) will be presented which is believed to be representative of all the various interests.

1–6. PERFORMANCE OF EQUIPMENT IN A NUCLEAR ENVIRONMENT

Because adequate shielding cannot always be provided for protection of vital components from nuclear radiation, attempts are being made to develop components and systems with greater radiation resistance. In addition, various agencies are engaged in efforts to provide procedures and data whereby the capability of current military equipment to survive nuclear radiation may be predicted. It is anticipated that these programs will lead to the development of new design procedures and concepts to improve the radiation resistance of equipment.

1–7. DETONATION

Programs in this area are concerned with various aspects of the physics of the detonation process. The initiation of high explosives by pressure waves transmitted across air gaps or metal barriers is of particular interest. Other programs are concerned with the effects of externally applied electric and magnetic fields

upon detonation, and with the development of explosive-electric transducers.

1–8. HYPERVELOCITY IMPACT

Impact between small fragments and structural targets is currently of interest for velocities up to 50,000 ft/sec. Satellite and ICBM vehicles make this order of magnitude of velocity technically feasible. Current activities in this field are directed toward means for attaining such velocities in the laboratory. Velocities of 20,000 ft/sec. are presently attainable, and efforts are being expended in developing a better understanding of the phenomena exhibited in this hypervelocity range.

1–9. SHAPED CHARGES

Current interest in the shaped charge field is centered in efforts to improve the theory relating design and performance of this type of weapon. One problem receiving attention, for example, is the design of liners to compensate for the deleterious effects produced by the spin of the projectile.

1–10. GROUND SHOCK

Research in ground shock phenomena is continuing, utilizing both laboratory and field test techniques. Efforts are being made to improve both measurement and scaling techniques, as well as to determine the dynamic stress-strain properties of various transmission media.

1–11. AIR BLAST

Extensive programs are currently active in order to determine the effect of blast waves on structures. Shock tube facilities are being used to study diffraction loading and target dynamic response. High-speed track facilities are being used to realistically simulate the interaction of blast waves and the transonic and supersonic flow fields of airfoils.

1–12. WOUND BALLISTICS

The objective of this continuing program is to provide a knowledge of the wounding potential of fragments, bullets, and other damage mechanisms. A quantitative basis for the assessment of wounding potential is necessary for the design of effective antipersonnel weapons.

Section III—References

1. E. S. Farrow, *Military Encyclopedia,* published by the author in 1885, (Unclassified).
2. L. H. Campbell, Jr., *The Industry-Ordnance Team,* Whittlesey House, 1946, (Unclassified).
3. —— *Annual Report 1959,* BRL, Aberdeen Proving Ground, Maryland, (Confidential), ASTIA No. AD316 874.

Chapter 2 (S)

KILL MECHANISMS

Section I (C)—Fragments

2–1. (U) INTRODUCTION

Fragmentation is the disruption of a metal container by a high explosive filler. Its purpose is to produce the optimum distribution of a maximum number of high velocity lethal fragments. Due to the use of the high explosive filler, fragmentation is always accompanied by blast.

The fragment acts as a kill mechanism by impacting the target at high velocity with its mass and forcing its way through the target material. The kinetic energy of the fragment at the time it strikes the target is one measure of its lethality. However, what constitutes the optimum fragment mass, velocity, and distribution of fragments will vary according to the target, be it a human, truck, airplane, building, satellite, etc.

It is generally desirable to have a shell or bomb body break up into pieces no larger than are required to "kill" the particular target. This arrangement provides the maximum number of effective fragments, by avoiding fragment sizes that are larger than necessary. Fragments are employed in projectiles in three different ways, as uncontrolled fragments, controlled fragments, and preformed fragments. Each of these three different types is discussed in following paragraphs. Special attention is also given to the effects of changes of velocity.

2–2. (U) PRINCIPLES OF OPERATION

To understand the mechanism involved in a fragmentation weapon, it is necessary to know what happens to the fragment between the time of weapon detonation and the time of fragment arrival at the target. Upon detonation of the explosive charge, the detonation wave causes the explosive and its case to swell until the failure point is reached. The case then fails in shear and tension, and fragments are ejected at high velocity. The fragments achieve an initial velocity and form a pattern (or beam) dependent primarily upon the physical shape of the casing. Aerodynamic drag forces slow the fragments during their flight to the target, as do the retardation effects of any target shielding penetrated prior to impact with the target. The area effectively covered by the beam of fragments depends to a large extent on the angle of fall of the projectile and the range to the target.

The fragments produce damage by penetration of a target. Upon impact with a hard target, such as steel or concrete, the kinetic energy of the fragment is transferred to the target material. If the energy transferred by the fragment is great enough to stress the target beyond its limit, penetration takes place. The kinetic energy is transmitted to the target from the fragment through the contact area, or presented area, of the fragment. For fragments of equal mass and velocity, the one with the least presented area will penetrate more extensively, due to the higher concentration of energy transfer.

Upon impact with a soft target, such as the human body, the fragment penetrates with much less loss of energy and often passes completely through the body. The effectiveness of the fragment depends upon the amount of energy lost to the target during fragment travel within the target. The shape of the fragment may be more significant in a soft target than within a hard target, because the shape will influence the path of the fragment and the rate of energy transfer. Relative to a given target, the penetrating power of a fragment is dependent, therefore, upon its mass,

shape, and striking velocity. A discussion of the effectiveness of fragments against soft targets is included in Ch. 3, Par. 3–3. The discussion of basic fragmentation and penetration data is found in Ch. 4, Sec. III.

2–3. (U) UNCONTROLLED FRAGMENTS

2–3.1. Description

Many items of explosive ordnance are designed to produce uncontrolled fragments as the primary kill mechanism. When the casing of a bomb, shell, warhead, or grenade is ruptured by the detonation of its high explosive filler, portions of the casing are propelled outward at high velocity. These segments of the casing are known as fragments. When no provision is made in the design of the projectile to control the size and shape of the segments, the segments are termed uncontrolled (or natural) fragments. The casting and explosive materials, charge-to-metal ratio, casing thickness and configuration, point of detonation, etc., determine the characteristics of the fragments.

Within some degree of probability, the fixed characteristics of the fragments are the number of fragments, initial velocity, weight distribution, and spatial characteristics. Those characteristics which differ with ambient conditions are blast and the retardation of fragments.

2–3.2. Examples

Two typical examples of uncontrolled fragmentation devices are a high explosive (HE) artillery shell and a general purpose (GP) bomb. The high explosive capacity of a bomb or shell will vary according to its mission and method of projection. A shell designed to be fired from a high-velocity tank gun must have thicker shell body walls, and consequently less explosive content, than one designed for use in a low-velocity howitzer or mortar (Ref. 1). The thicker walls are required to withstand the higher acceleration forces encountered at the time of firing. The bursting charge capacity of a bomb will depend upon its mission: an armor-piercing bomb must have much thicker walls than a general purpose bomb. A light-case bomb has thinner walls than the GP bomb, and sacrifices fragmentation effect for increased blast effect.

Shells, bombs, and fragmentation grenades basically consist of a metal casing, a high explosive filler, and a fuze. The casing is usually steel, and an explosive such as trinitrotoluene (TNT) may be used as the high explosive. Various fuzes are employed, depending on the delivery mechanism and the target characteristics. Since fragmentation devices are designed to be detonated near, rather than upon striking, the target, proximity (VT) fuzes are often employed.

2–4. (U) CONTROLLED FRAGMENTS

2–4.1. Description

Controlled fragments are produced by warhead casings designed to break up in specific patterns. The fragment takes on its final individual shape during the expansion of the products of explosive detonation. Some of the methods employed to achieve various degrees of control consist of: multiple wall casings; casings made of a series of rings, or helically wrapped wire, where the rings or wire may or may not be notched (grooved); casings that are scored (grooved) in one or two directions; and fluted liners inserted between the charge and the casing to focus the detonation on the casing in a desired pattern.

2–4.2. Advantages

Through the use of controlled fragments, the amount of casing metal that is wasted in fragments too small to be effective, or larger than necessary, is kept to a minimum. The most efficient fragment size and shape for use against a specific target can be selected, and optimum fragment pattern and initial velocity can be approached within practical limits.

The mechanics of kill by a controlled fragment is identical to that of an uncontrolled fragment; however, controlled fragments offer the advantages listed below:

1. The performance of controlled fragments can be predicted more accurately.
2. When the parameters affecting penetration (velocity, mass, and shape) are con-

trolled, greater damage will be inflicted to a target for which the weapon is designed.

3. Fragments with better aerodynamic characteristics can be employed, resulting in higher impact velocities and greater penetration.

2-5. (U) PREFORMED FRAGMENTS

The most complete control of fragment size and shape is achieved by the use of preformed, or precut, fragments. Preformed fragments, formed during weapon fabrication, exist in their final shape before detonation of the explosive charge, and they are mechanically held in their proper orientation around the charge. When preformed fragments are used in a properly designed warhead, breakage of fragments upon expulsion and adhesion of fragments to each other may be considered negligible, and nearly 100 per cent fragmentation control is achieved.

Typical shapes used for preformed fragments are cubes, rods, spheres, and flechettes (in-stabilized darts or needles). They cause damage by penetration, as is the case with all fragments. In the same manner in which controlled fragments offer advantages over uncontrolled fragments, preformed fragments may closely approach optimum fragmentation effects for a specified target, because nearly complete control of fragment mass, shape, and velocity can be designed into the weapon.

2-6. (U) SECONDARY FRAGMENTS

Secondary fragmentation results from breakup of either controlled or uncontrolled fragments upon impact, or from the creation of fragments from the target material when it is impacted by a projectile. One important example of secondary fragmentation is the spalling of armor plate when it is pierced by armor-piercing shot. The fragments or spalls are broken off the back of the plate and become significant kill mechanisms within the armored enclosure. Another example of secondary fragmentation is the break-up of human bone structure upon the impact of a penetrating missile. The bone splinters or fragments may cause more overall damage within the human body than did the original missile.

2-7. (C) CONTINUOUS RODS

Continuous rods represent a specialized extension of fragmentation techniques, in which discrete rod fragments are replaced by a bundle of metal rods. The rod bundle is arranged in the form of a hollow cylinder with the rod axes parallel to the cylinder axis. Alternate rod ends are welded together to form a continuous expanding ring when the rods are launched at high velocity by a central cylindrical, or annular, high explosive charge. As the bundle of rods expands outward from the point of detonation it forms a continuous and expanding hoop, which eventually breaks up into several pieces as the hoop circumference approaches and exceeds the total of the rod lengths. The cutting ability of the rods is a function of the rod hoop weight and its velocity. A warhead of this type can produce severe structural and component damage against a large light-frame target. For this reason, its considered use is against aircraft targets (Ref. 2).

2-8. (C) HYPERVELOCITY FRAGMENT IMPACT (Refs. 3 and 4)

2-8.1. (U) Description

Observations of the effects of increases in fragment velocity have revealed three general conditions of impact, characterized by the behavior of the fragment and target material. In the low velocity condition, the fragment remains intact and the cavity produced in the target may be only slightly larger in diameter than the fragment. As the striking velocity increases, the dynamic pressures encountered exceed the strength of the fragment, which begins to break up, initiating the transitional condition. This causes the penetration to increase more slowly with increasing velocity; in some cases it causes an actual reduction in the penetration with increasing velocity. As the striking velocity increases further, the penetration again increases, proportional to a fractional power of the velocity (usually between ⅓ and ½). The crater formed approaches a hemi-

spherical shape, and the hypervelocity or fluid-impact condition begins.

The term hypervelocity, when used in the terminal ballistics sense, is applied to the crater-formation phenomenon, rather than to a specific impact velocity. One criterion for the onset of hypervelocity is that the cavity shape must be approximately that of a hemisphere. No single numerical value can be assigned for the beginning of this velocity range, as the velocity is a function of the strength characteristics of both the target and the fragment materials. Hypervelocity fragments and cratering are discussed in detail in Ch. 4, Par. 4–13.

2–8.2. (U) Effect of Hypervelocity Impact

The transition condition of hypervelocity impact is clearly demonstrated in the case of a steel projectile impacting on a thick lead target. The penetration increases roughly as the first power of the velocity up to about 0.5 km/sec. (1640 ft/sec.), and then decreases as the inverse first power of velocity up to about 0.8 km/sec. (2600 ft/sec.). Penetration of the steel projectile into the lead then increases again, proportional to the $\frac{1}{3}$ power of velocity. It is interesting to note that the penetration does not rise to its earlier maximum value until the impact velocity reaches 2 km/sec. (6560 ft/sec.), which is a fourfold increase. The actual cavity volume continues to increase with velocity increase, but its shape is changing to become more nearly hemispherical. The velocity boundaries and detailed character of the transitional condition are not well defined, and differ markedly with target and projectile material. The transitional condition has been associated with the plastic wave velocity for the target material, but it would seem that a more important factor would be the impact pressures determined by the velocity and target density as well as the strength of the projectile.

In the true hypervelocity impact condition, it is expected that the crater formed in a semi-infinite target will be hemispherical, independent of the ratio of projectile and target densities and, to a considerable extent, independent of the projectile shape except in the case of large length/diameter ratios. These features seem to be confirmed by experimental results, to date.

2–8.3. (C) Stages of Crater Formation

(C) Three stages have been identified in the formation of the crater in the hypervelocity condition, as a result of experimental work in which flash X-ray photography is employed. Initially, the mechanism appears to be a hydrodynamic one in which both the target and the projectile flow plastically during the primary stage, and the kinetic energy of the projectile is transferred to the target. This primary stage persists for only a small fraction of the total time of crater formation. During the primary stage, the pressures generated are of the order of millions of atmospheres, and the density of the target and projectile behind the shock front may be appreciably increased. For example, calculations for the impact of iron on iron at 5.5 km/sec. indicate that the maximum pressure is about 2 megabars, which corresponds to a density ratio of about 1.4.

(C) After the pellet has been completely deformed and lost its integrity, the energy is transferred to the target in the form of a plastic deformation wave. The cavitation continues for a period that depends on the amount of energy transferred.

(U) Finally, there is a plastic and elastic recovery stage which follows the immediate crater formation. Craters in 2SO aluminum have been observed to recover about 30 per cent by volume.

(U) The great bulk of experimental work in hypervelocity impact has been devoted to the study of crater formation in essentially semi-infinite targets, in an effort to develop an understanding of the basic phenomena. However, studies have indicated that, if the penetration in a semi-infinite target is p, complete penetration of a plate of thickness up to 1.5 p may be obtained with the same projectile and impact velocity. In a marginal hypervelocity penetration, however, the projectile or fragment itself does not carry through, but spalling and some flow of the target material will be produced and may be sufficient to cause damage to internal components.

Section II (C)—Solid Projectiles

2–9. (U) INTRODUCTION

Solid projectiles, like fragments, act as kill mechanisms by their penetration of a target. The term "kinetic energy (KE) projectiles" is often used to refer to solid projectiles, because their terminal effects are dependent upon the kinetic energy of the projectile at the time it strikes the target. Examples of solid projectile types are: bullets, armor-piercing shot, single flechettes, knives, and arrows.

Unlike the fragment, the solid projectile is usually fired singly (one projectile per round fired), has a sharp or relatively sharp tip, and is launched in a path directly at the target. In contrast to this, the fragment is produced multiply as a result of an explosion, has no particular penetrating surface, and reliance is placed upon a number of fragments, distributed in space, to hit the target. The solid projectile is also differentiated from the explosive "shell," whose terminal ballistic effects depend on blast and fragmentation, rather than the kinetic energy of the projectile.

2–10. (U) BULLETS

Bullets are classed as solid projectiles fired from small arms weapons, usually limited to caliber .50 and below. There are several types of bullets, used for various purposes, the service types being ball, armor-piercing, tracer, incendiary, and armor-piercing incendiary. Special purpose types are used for testing and practice, but will not be considered here. Bullets have a metal core and a gilding metal jacket, and some have a filler in the point or base, or both. Fig. 2–1 illustrates some typical bullet types.

Ball ammunition is effective against personnel or light materiel. The bullet is usually comprised of a core, composed of an antimony-lead alloy, and a gilding metal jacket. Caliber .50 ball ammunition bullets, however, use a core of soft steel to provide ballistic properties similar to the armor piercing bullet (Ref. 5).

The kill mechanism of ball ammunition against both hard and soft targets is the same as that previously described for fragments. That is, the penetration and amount of damage is a function of the shape, weight, and striking velocity of the bullet. When used against light target materials, ball ammunition may produce secondary fragments that are effective against personnel located behind the target.

Armor-piercing bullets contain a hardened steel core and a point, or base, filler of lead or aluminum between the core and the jacket. They are designed for use against armored aircraft and lightly armored vehicles, concrete shelters, and other bullet-resisting targets. Armor-piercing bullets employ the same kill mechanisms as ball type ammunition, that is, penetration into hard and soft targets and the production of secondary fragments. Armor-piercing bullets have greater penetrating power than other types of standard ammunition due to the presence of the hardened steel core. This core resists deformation upon impact with the target and thus maintains a smaller impact area, resulting in a longer duration of highly concentrated forces.

Tracer bullets contain a chemical composition in the rear which is ignited by the propellant charge and which burns in flight. The forward half of the bullet contains a lead slug. Tracer ammunition is primarily used for observation of fire. Secondary purposes are for incendiary effect and for signaling.

Incendiary bullets contain an incendiary which is ignited upon impact. Armor-piercing incendiary (API) bullets are designed to "flash" on impact and to then penetrate armor plate. The main kill mechanism is the penetration of fuel cells and the ignition of the fuel in the target. Destruction is accomplished by the combined use of kinetic-energy impact and fire.

2–11. (C) FLECHETTES

Flechettes are fin-stabilized solid projectiles with a length to diameter ratio much greater than that of a bullet. The general configuration and nomenclature are shown in Fig. 2–2. Fle-

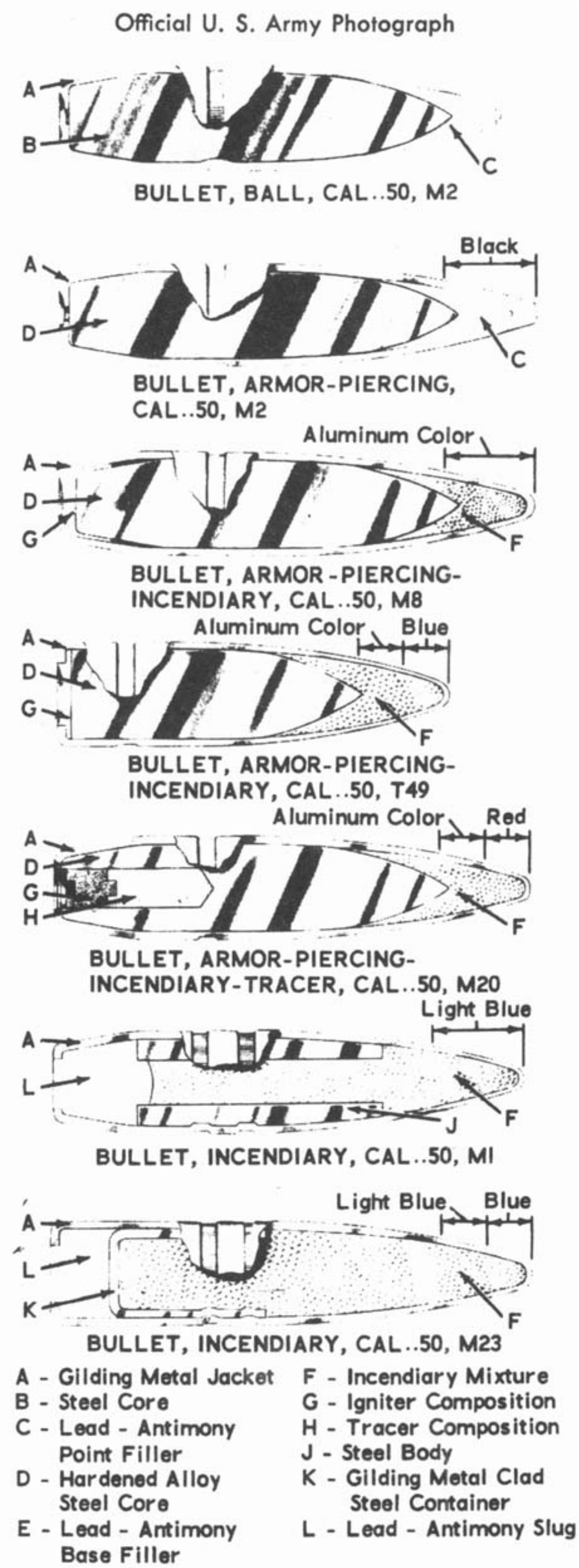

Figure 2–1. Bullets

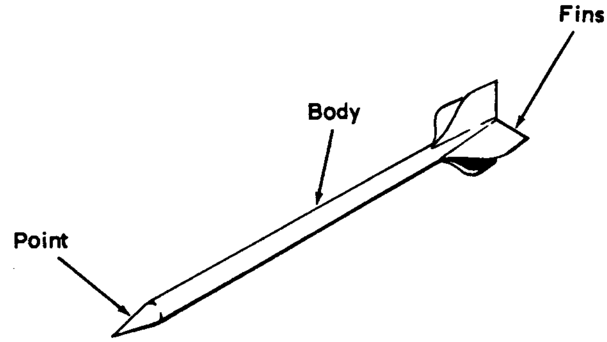

Figure 2–2 (C). Flechette Configuration (U)

chettes, sometimes called darts or needles, are made in a variety of materials, sizes, and shapes. Fin forms vary widely with manufacturing techniques and application, and may be straight, or canted to provide spin in flight, or on-center or offset to conform to special packing requirements. Many point shapes are utilized for improving terminal ballistics effects against specific targets (Ref. 6).

Flechette employment may be divided into two major categories: as used in antipersonnel warheads; and as used in small arms ammunition, in either scatter-pack cartridges or individual projectile rounds. In antipersonnel warheads, the flechettes offer advantages over cubes and similar fragments by their superior aerodynamic characteristics and penetrating power. Damage is achieved by penetration and perforation, and is enhanced by the higher long-range striking velocity of the flechette. This permits more fragments of lower unit mass to be incorporated in a fragmentation warhead, providing better area coverage.

In small arms ammunition a pack of flechettes may be used in what is known as a scatter or salvo round, or a single flechette can be employed to provide a cartridge of small size and light weight. The scatter rounds are foreseen as particularly adaptable to short range weapons, such as shotguns or caliber .45 hand arms, to provide increased probabilities of hit. The single flechettes provide a relatively flat trajectory projectile for long ranges.

The flechette may be made lighter in weight than a bullet, yet obtain comparable lethality, because the light flechette can be launched at

higher velocities than the bullet for the same gun pressure and will retain its velocity for longer ranges. The smaller frontal area of the flechette enhances its penetrating power and, if its remaining velocity is sufficiently high, it will tumble within a soft target and transfer its energy to the soft target at a greater rate than a bullet. For impacts at velocities below that at which tumbling occurs, the flechette wounds by cutting permanent slits that are comparable in size to the lateral dimensions of the fins.

Flechettes appear to have good characteristics with respect to penetration of hard targets, but additional studies are required for a complete analysis. Additional studies are also required on the action of flechettes within soft targets, and on the factors affecting tumbling.

2-12. (U) ARMOR-PIERCING (AP) PROJECTILES

Armor-piercing projectiles achieve their terminal effect by forcing their way through the target material under the impetus of kinetic energy, as do fragments, bullets, and flechettes. Armor piercing "shot," for example, is a solid projectile without a bursting charge, for use with cannon, and thus differs physically from bullets, even though both may be armor-piercing.

Armor-piercing projectiles are designed specifically to attack hardened targets such as armored vehicles, and are sometimes used against reinforced structures. For this reason they are characterized by high accuracy and high velocity (a flat trajectory resulting from short time of flight), because of the importance of achieving a first-round hit (Refs. 1 and 7). Armor-piercing projectiles are discussed in more detail in Ch. 6, Par. 6-5.2.

2-13. (U) HIGH EXPLOSIVE PLASTIC (HEP) ROUNDS

High explosive plastic rounds achieve their terminal effect by spalling the interior surface of armor plate. This type of round is discussed in detail in Ch. 6, Par. 6-5.4.*b*.

2-14. (U) KNIVES, BAYONETS, AND ARROWS

Knives, bayonets, and arrows are sometimes used in combat. They are suitable for use against personnel, but require considerable skill in handling in order to achieve a kill.

Knives and arrows have been used in recent times in order to attack sentries and outposts when silence has been necessary. Bayonets have been used in hand-to-hand combat, but remain a weapon of last resort. It may be necessary for a soldier to resort to the bayonet in close combat should he not have time to reload his rifle.

Section III (S)—Shaped Charges

2-15. (U) INTRODUCTION

The performance of the shaped charge missile in no way resembles that of the kinetic energy projectile. Its effect is due entirely to the formation of a high velocity jet of gases and finely divided metal, which becomes the penetration medium. The thickness of material that can be penetrated is essentially independent of the projectile's striking velocity. The projectile case remains at the outer face of the target.

A shaped charge missile consists basically of a hollow liner of inert material, usually metal, that is a conical, hemispherical, or other shape, backed on the convex side by explosive. A container, fuze, and detonating device are included (Fig. 2-3).

Shaped charge projectiles intended for use against armored vehicles are often designated by the letters "H.E.A.T.," which stand for "*H*igh-*E*xplosive *A*ntitank." The abbreviation is often reduced to "HEAT," which has been interpreted by some to infer that the projectile burns its way through the armor. This is not a correct assumption; the letters are simply an abbreviation which, by coincidence, spells out a common word.

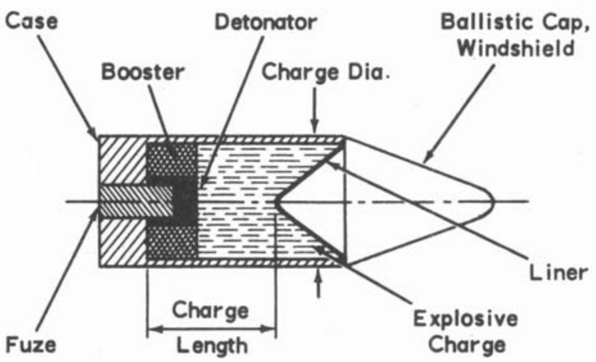

Figure 2–3. Shaped Charge Projectile, Schematic Diagram

2–16. (U) PRINCIPLES OF OPERATION

When the shaped charge missile approaches or strikes a target, the fuze (proximity or contact) detonates the charge from the rear. A detonation wave travels forward and the metal liner is collapsed, starting at its apex. The collapse of the liner cone results in the ejection of a long, narrow jet of metal particles from the liner, at velocities from 10,000 to 39,000 ft/sec.

This process is illustrated in Fig. 2–4 by the series of ultra-high speed radiographs of an experimental shaped charge lined with a 45-

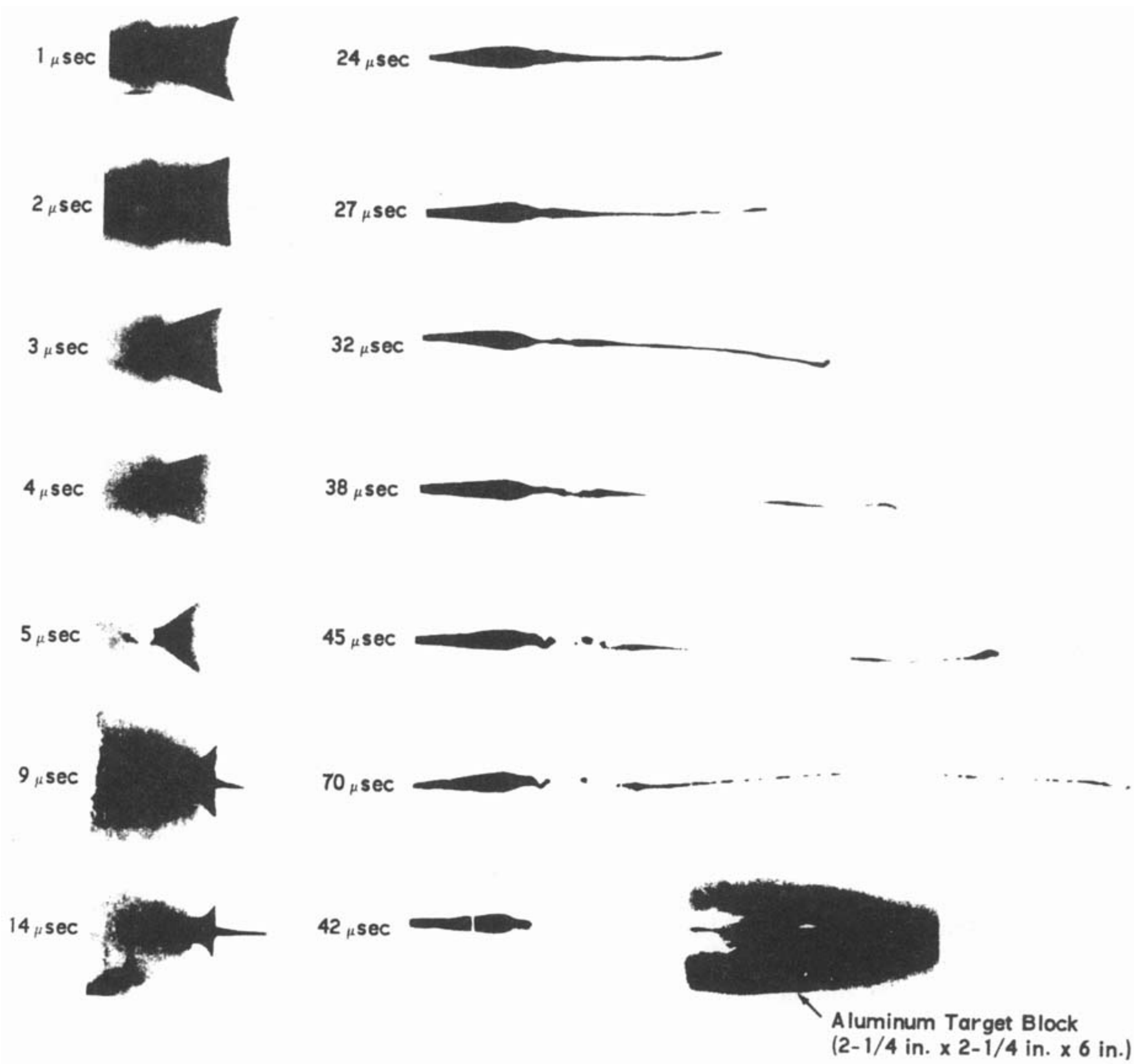

Figure 2–4. Ultra-High Speed Radiograph of Shaped Charge Detonation

degree steel cone, radiographed at successive times to depict the mechanism of cone collapse. The charge was 50/50 Pentolite, having a base diameter of ¾ inch. The time, noted in microseconds for each radiograph, denotes the time after the detonation wave passed the apex of the liner cone. There is a gradient in the velocities of the elements of length along the jet. The elements in front move faster than those in the rear, thus causing the jet to lengthen, thereby reducing its average density with time. The jet is followed by the major portion of the now completely collapsed cone. The latter is often referred to as the "slug," or "carrot," because of its peculiar shape.

The description of the principles of operation of the shaped charge, given above, is general in nature. Shaped charge design involves numerous, variable parameters. It should be recognized that considerable latitude exists in the choice of these parameters; but also that many permutations of these could (and should) result in the same net effect.

2-17. (U) JET PENETRATION

When a jet strikes a target of armor plate or mild steel, pressures approximating 250,000 atmospheres are produced at the point of contact. This pressure produces stresses far above the yield strength of steel; consequently, the target material flows out of the path of the jet as would a fluid. There is so much radial momentum associated with the flow that the diameter of the hole produced is considerably larger than that of the jet. The difference in diameter between the jet and the hole it produces depends upon the strength characteristics of the target plate. Thus, a larger hole is made in mild steel than in armor plate, and the penetration depth in a very thick slab of mild steel can be as much as 30 per cent greater than in homogeneous armor.

As the jet particles strike, they are carried radially with the target material. Thus, the jet is used up from the front, becoming shorter and shorter, until finally the last jet particle strikes the target and the primary penetration process stops. The actual penetration continues for a short time after cessation of jet action, because the kinetic energy imparted to the target material by the jet must be dissipated. The slight additional penetration caused by this afterflow is called secondary penetration. Its magnitude depends upon target strength, and accounts for the differences observed between the depths of penetration in mild steel and in homogeneous armor, although there is probably some difference in the primary penetration as well.

While some exceptions will be found to the following rule, the depth of primary penetration, P', depends mainly on several factors: the length of the jet, L; the density of the target material, ρ_t; and the average density of the jet, ρ_j. It has been found that P' is proportional to $L\sqrt{\rho_j/\rho_t}$, giving

$$P' \cong KL\sqrt{\rho_j/\rho_t} \qquad (2\text{-}1)$$

The jet density, ρ_j, is proportional to the density of the cone liner material, particles of which are dispersed throughout the primary jet.

2-18. (C) PENETRATION FACTORS (Ref. 1)

2-18.1. (C) Type, Density and Rate of Detonation of Explosive Charge

While the depth of penetration is indicated to be more closely related to detonation pressure than to the rate of detonation, because of interdependence of effects it may be said that the greatest effect will be produced by that explosive having the highest rate of detonation. Table 2-1 illustrates the relative effect of four different castable explosives.

Although the rate of detonation is of prime importance in selecting a high-explosive filler,

TABLE 2-1 (C). DETONATION RATE COMPARED TO PENETRATION FOR FOUR CASTABLE EXPLOSIVES (U)

Explosive	Density (grams/cc)	Detonation Rate (m/sec.)	Relative Standing in Penetration Efficiency
Comp B	1.68	8,000	1
Pentolite	1.64	7,640	2
Ednatol	1.62	7,500	3
TNT	1.59	6,900	4

other properties of the explosive must be taken into consideration. Among these are sensitivity to initiation, pourability, and thermal stability.

2–18.2. (C) Confinement of Charge

Confinement is inherent in a military projectile, whether it be the relatively heavy confinement found in the shell thickness of the 105-mm Howitzer, or the thin-gage wall of the bazooka rocket. Also, the confinement effect is noted whether the confinement is provided by an increased wall thickness or by a "belt" of explosive. Its effect on shaped charge action is to decrease lateral loss of pressure, and to increase the duration of application of pressure. This results in a more efficient shaped-charge collapse, and, therefore, increased hole volume or depth in the target material. As a matter of design compromise the wall may be quite thin in order to provide a lighter projectile, thus obtaining a higher muzzle velocity, which should increase the hit probability. However, the thinner wall results in less depth of target penetration.

2–18.3. (C) Shape, Diameter, and Length of Charge Back of Liner

The length of the projectile body, and hence of the charge, is most frequently limited by aerodynamic performance and projectile weight specifications. In general, the penetration and the hole volume obtained increase with increasing charge length, but reach a limit at about 2 or 2.5 charge diameters. (Charge length is measured from the apex of the liner to the rear of the explosive charge.) Existing shaped charge designs usually have one of the shapes shown in Fig. 2–5. Although each can be made to perform satisfactorily, type (A) has the advantages of increased amount of high-explosive, which could result in increased secondary effects of blast and fragmentation. Types (B) and (C) are sometimes necessitated by the requirements for a lighter projectile weight, in order to increase muzzle velocity and accuracy.

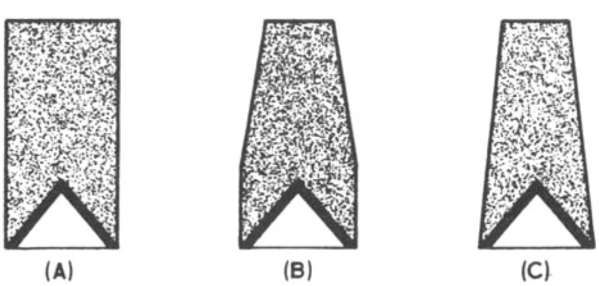

Figure 2–5. Shaped Charge Body Designs

2–18.4. (C) Liner Material and Thickness of Liner

The shaped charge effect is not dependent on the presence of a liner, but because the penetration of the jet is proportional to the square root of its density, the material of the liner enhances the effect by increasing the density of the jet. Increased depth of penetration is obtained as the liner is made thinner, but thin liners require much closer manufacturing tolerances than the thicker ones. The net effect of these contradictory factors is that the penetration depth will increase up to a maximum as the liner thickness is decreased (Fig. 2–6), at which point the manufacturing imperfections will become more important, and

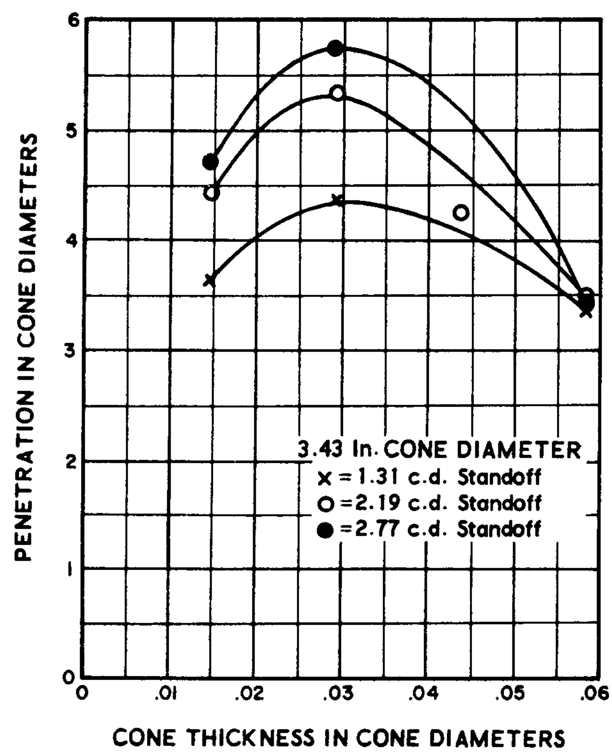

Figure 2–6 (C). Penetration vs Standoff and Liner Thickness (U)

further decreases in liner thickness result in less penetration. The alloy of the metal to be specified for the cone should generally be that which has the greatest ductility. Copper, steel, and aluminum have all been used. Fig. 2–7 shows the variation in penetration, as a function of standoff, obtained with liners made of these materials. (Refer to Par. 2–18.8 for a definition of "standoff.")

2–18.5. (C) Liner Shape

Differently shaped liners and cavities react in different ways. For example, a conical liner (Fig. 2–8) collapses from the apex and approximately 70 per cent to 80 per cent of the liner follows behind the jet as a slug. Hemispherical liners appear to turn inside out, most of the liner being projected in the jet. However, the best and most consistent results have been obtained with conical liners. This may be because it is more difficult to maintain close tolerances with shapes other than conical. Double-angle conical liners are also being investigated. Firings early in the study of double-angle cones, with cones in which the change from one angle to another was made abruptly, did not show any increase in penetration. However, with cones in which the change from one angle to another was made smoothly, and the liner wall was tapered, peak performance was obtained at normally available standoffs.

2–18.6. (C) Effects of Rotation Upon Jets

The rotation in flight of a spin-stabilized, shaped-charge projectile with a simple liner, as previously described, causes a large decrease in penetration. This effect is especially noticeable at large standoff. In the process of jet formation from a rotated liner, there is induced not only the typical, linear velocity gradient found in all shaped charges, but an additional rotational velocity gradient as well. The base of the cone has a higher tangential velocity than the apex. Consequently, when the cone col-

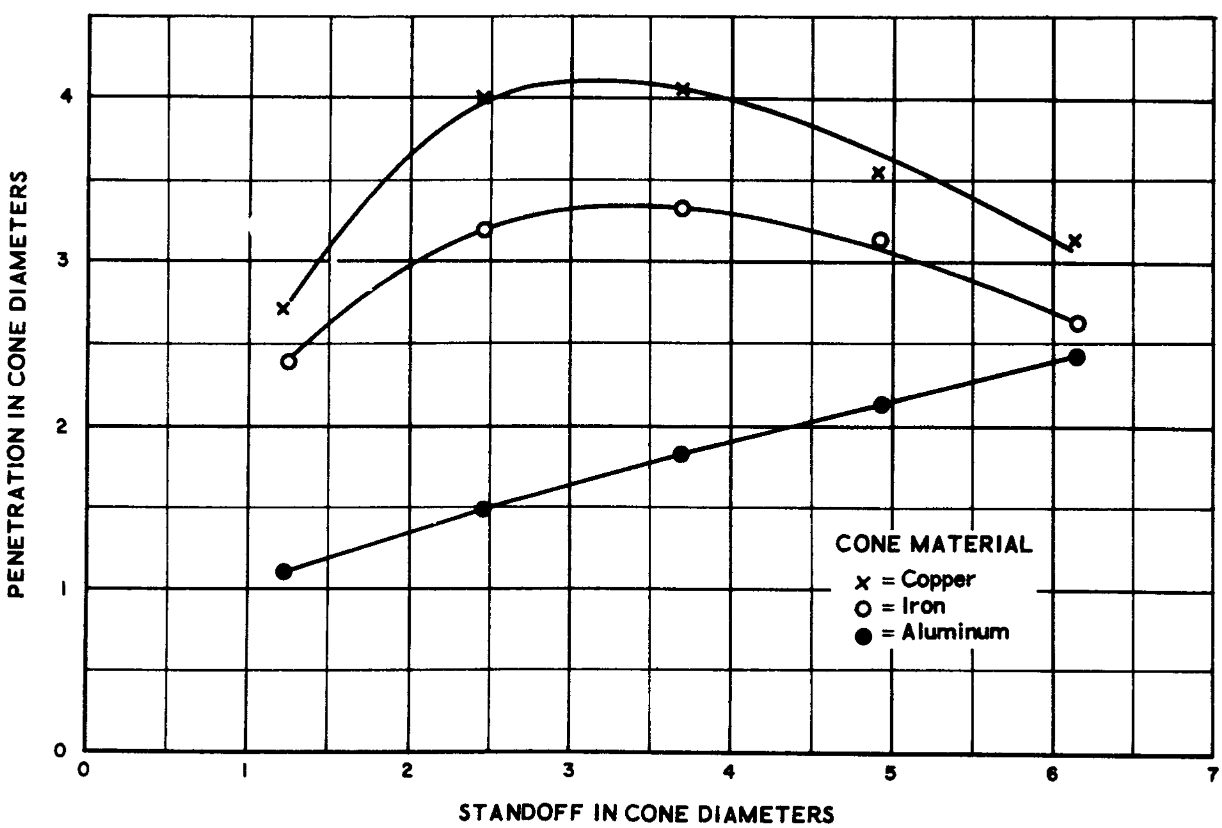

Figure 2–7 (C). Penetration Obtained with Different Liner Materials (U)

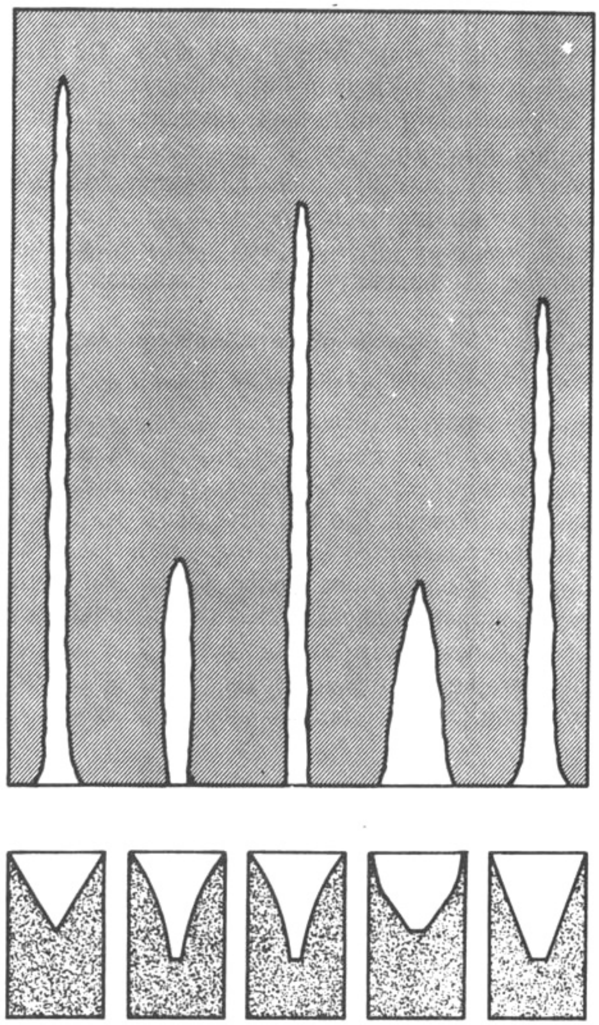

Figure 2–8 (C). Typical Liner Shapes and Hole Profiles (U)

lapses, the faster-moving particles of the cone base form the tail end of the jet. The rear end of the resultant jet is, therefore, rotating faster than the forward end, and the rotational velocity should show a continuous decrease from the rear of the jet to the forward tip. As long as the jet is continuous, therefore, it may be considered as being subjected simultaneously to tension resulting from the linear velocity gradient, and to torsion produced by the rotational velocity gradient (Ref. 8).

It is possible to study in detail the deterioration of the jet by the use of triple-exposure flash X-ray pictures of detonated, shaped charges. The observed, detailed effects of rotation are illustrated by the radiographs shown in Fig. 2–9. Part (A) of the figure shows three views, 60 degrees apart, of the normal jet from an unrotated, 105-mm, smooth, copper liner of good quality. Part (B) shows three views of a jet from a similar liner rotating at 15 rps. These show the marked tendency toward ellipticity of the transverse cross-section of the jet, as well as an early incidence of jet break-up.

Part (C) of the figure shows, at 30 rps, the incidence of the "bifurcation" phenomenon. (Bifurcation is the radial break-up of the jet

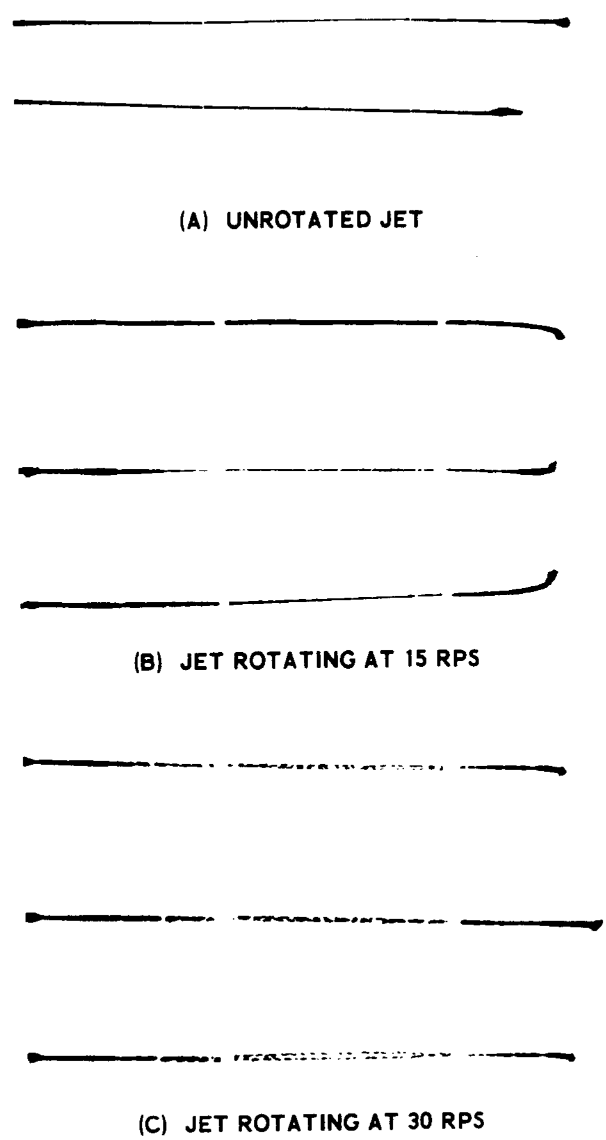

Figure 2–9 (C). Effects of Rotation upon Jets (U)

into two distinct jets.) The two separate portions of the bifurcated jet appear to lie in a plane. The same charge, detonated at 45 rps, produces bifurcated portions which no longer lie in a plane but appear to lie along a helical surface. Experimental observations indicate that at rotational frequencies considerably in excess of 60 rps, the process of bifurcation gives way to "polyfurcation." (Polyfurcation is the radial break-up of the jet into more than two distinct jets.)

In order to counteract the rotational frequencies of the jet, it is necessary to impart to each element of the liner, by some means, a tangential component of velocity which is equal in magnitude but opposite in direction to that set up by the initial spin of the liner. The simplest means of accomplishing this is to find a way of using the energy of the explosive to produce a counter-torque on the liner.

Attempts have been made to improve the performance of spin-stabilized shells by using various non-conical, axially-symmetric liners. However, such attempts have not been promising at high rates of spin; therefore, the major emphasis has been on the design of fluted liners not having axial symmetry.

The idea underlying the use of fluted liners is that of spin compensation to destroy the angular momentum of the liner, to inhibit jet spreading. The fluted-liner method of spin compensation is based on two phenomena. One, sometimes called the "thick-thin" effect, is the observed dependence upon the thickness of the liner of the impulse delivered to a liner element by the product gases of detonation. The second, named the "transport" effect, is the dependence of the impulse delivered to the liner upon the angle at which the detonation products impinge on the liner.

Application of the thick-thin effect to a fluted liner is illustrated in Fig. 2–10. The impulse per unit area is always greater on the offset surface, because the thickness normal to that surface is greater. Furthermore, the impulse is directed along the surface normal. When the impulses delivered at all surface elements are resolved into radial and tangential components, and summed, the total tangential component has a net resultant which produces a torque, in

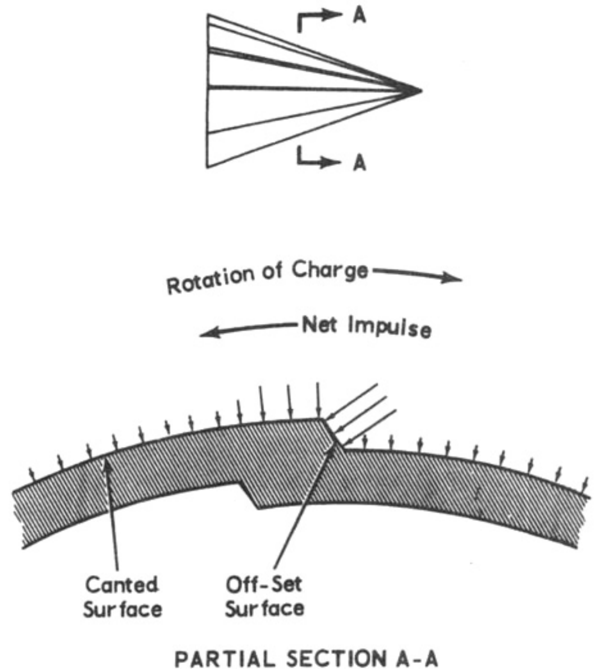

Figure 2–10 (C). Fluted Liner Configuration and Active Forces (U)

the direction shown, which can be used for spin compensation.

Also shown in Fig. 2–10 is the effect of the impulse delivered to the canted surface. The effect is significant in spin compensation because a torque is produced in the direction opposite to that produced by the thick-thin effect. However, because the angle at which the detonation wave strikes the canted surface is usually less than that for the offset surfaces, the net torque produced is in the direction of the forces acting on the offset surface.

A fluted liner is designed to compensate for the angular momentum of a particular projectile, thus, the caliber, charge diameter, and spin rate of the projectile are determining factors in selecting flute characteristics. A fluted liner spun at its designed optimum frequency produces a jet like that produced by an equivalent smooth liner fired statically. When fired statically, the fluted liner produces a jet like that from a rotated smooth liner.

Other methods of spin compensation have been tried, such as spiral detonation guides, fluting the explosive instead of the liner, and the "built-in" compensation found in smooth,

Next Page

spun liners. These techniques have been found to produce some degree of spin compensation, but only the fluted liner has been found to hold much promise.

The elimination of spin degradation by means other than spin-compensation has also been the subject of experimentation. One method has been to design a shell so that it will be stable with a very low spin. This type of shell has increased drag, requires a special weapon with low-twist rifling, and still needs some kind of spin compensation.

The concept has been proposed of using peripheral jet engines on the shell to stop its spin before the target is reached. Computations of the required torque offer little hope that this method will prove practical.

Bearing-mounted charges that permit part of the shell to spin, for stability, while the charge itself spins only slowly, have been proven practical. However, a means is required to compensate for the low spin rate, as is a means to assure the uniformity of projectile spin rate.

Fin-stabilized rounds are commonly used as a means to avoid spin degradation. Even these types are often given a small amount of spin in order to improve their stability in flight; therefore, spin compensation is still required.

Any technique for reducing the rate of spin of a given projectile provides only an interim solution. As soon as a fluted liner can be designed to compensate for the frequency of spin of a standard round of the given caliber, it provides the most convenient and economical solution to spin-degradation for that caliber (Ref. 9).

2–18.7. (C) Fuze Action

The use of a suitable fuze is a major factor in the effective use of shaped charges that are to be activated on impact. The contact fuze must function quickly enough to detonate the charge before the cone liner becomes deformed, and before the projectile is deflected. This is vitally important when shaped charge projectiles strike high obliquity armor, because the speed of fuze action will affect the relative amount of surface armor area that is perforable. If the projectile is fuzed with an inertial-type base fuze, as shown in views (A) and (B) of Fig. 2–11, the inherent delay action of the fuze plunger may allow the projectile to ricochet before detonation, or permit collapse of the ballistic cap under forward inertia and cause an appreciable decrease in the standoff distance (Par. 2–18.8, below).

It is desirable to start initiation at the front end, at the instant of impact, and to transmit the impulse to the rear end so that the detonating charge may be initiated from the rear. However, this must take place much faster than occurs with the use of the inertia-type base fuze. There are two principal means of accomplishing this desired result. One uses the so-called "spit-back" (flash-back) fuze. In this fuze a small, shaped-charge explosive in the nose of the projectile is initiated by a percussion primer and fires a jet backwards, through a passage provided in the main charge, into a base booster. Because the velocity of such a small jet is very high, this fuze provides an extremely rapid method of transmitting the trigger action from the front to the rear. The other type of nose-initiated fuze is electrically actuated. In this type, often referred to as the "point-initiating base-detonating" (PIBD) type, crushing of the nose sets off an electrical impulse which is carried by wires to an electrical detonator at the rear of the projectile.

2–18.8. (U) Standoff Distance

One of the most important factors governing depth of penetration by shaped charges is the standoff distance. Standoff distance is the distance between the base of the liner and the surface of the target, at the instant of explosive initiation. This distance may be given in absolute terms, such as inches or millimeters, or may be expressed in terms of the charge diameter (i.e., 1½ charge diameters, 2 charge diameters).

Proper projectile design provides a standoff distance that allows time for the fuze to function properly and the cone to collapse, forming a jet of proper density, thus realizing the maximum capabilities of the projectile. View (C) of Fig. 2–11 illustrates the shaped charge technique as used in an anti-vehicle land mine. The distance from the top of the mine to the bottom

Chapter 3 (S)

TARGET VULNERABILITY

Section I (U)—Personnel

3–1. INTRODUCTION

Personnel are vulnerable to numerous kill mechanisms, the most important of which are fragments, bullets, flechettes, blast, toxic and biological agents, and thermal and nuclear radiation. Although personnel are vulnerable to each of the kill mechanisms in different ways, the end effect is to render the individual incapable of performing his intended function.

Fragments, bullets, and flechettes are considered as a single class of kill mechanism because all cause their results by penetration and/or perforation. These projectiles can penetrate into the major body cavities and limbs to cause damage to the critical tissues such as the heart, lungs, and brain, etc., thus causing loss of fine and coarse muscular coordination of the extremities. Their effects range from immediate death, to incapacitation through loss of the use of one or more limbs, to minor wounds which produce little immediate effect, but which can become incapacitating if no medical treatment is available.

3–2. INCAPACITATION CRITERIA

As defined by current lethality criteria, the incapacitation of a soldier refers to his inability to carry out his assigned duties. A soldier's combat duties are various and depend upon the tactical situation as well as his military assignment. Four military tactical situations have been chosen for defining incapacitation. These situations are assault, defense, reserve, and supply. The ability to see, hear, think, and communicate is considered as a fundamental necessity in all of the situations; loss of these abilities is assumed to be incapacitating.

Infantry soldiers in assault situations are considered to require the use of their arms and legs. The ability to run and to use both arms is desirable, and the ability to move about and to use at least one arm is necessary. A soldier cannot effectively participate in an assault if he cannot move about and if he cannot use hand-operated weapons. Thus, incapacitation is defined for the assault situation.

In a defense situation a soldier's need to move is considered minimal as long as he can operate hand weapons. His ability to relocate himself, although desirable, is not necessary to the performance of some valuable duties.

The third situation considered is that of troops held in reserve close to the combat zone, and ready to be committed to the assault or defense. They are considered to be more vulnerable to incapacitation than active combat troops, because they probably would not be committed to action even if the wounds received were relatively minor.

The final military situation is that of supply, which includes vehicle drivers, ammunition handlers, and a variety of other personnel, possibly far from combat. These troops would be hospitalized upon the loss of use of an arm or leg, or for even less severe causes, and are considered to be very vulnerable to incapacitation.

The time factor used in the incapacitation criteria is the length of time from the wounding to the occurrence of loss of muscular coordination sufficient to render a man ineffective in performing his mission. To illustrate the need for a time factor, consider a soldier in a defense position where it is not necessary that he move about. He is hit in the leg by a fragment which penetrates into the muscle and severs a peripheral artery. Although he may be limited in his ability to move, he is not considered incapacitated. However, if he has no

medical attention the loss of blood will, in time, prevent him from functioning effectively, and he must then be considered a casualty.

Psychological factors will have a definite effect on incapacitation and may even void the entire organic approach. Among these factors are the fear of the unknown, as experienced by "green" troops, the effect of enemy propaganda, apprehension caused by personal problems, and excessive loss of mental capabilities or of emotional stability due to prolonged exposure to physical danger or to an abnormally hot, cold, or wet battlefield environment. Owing to a lack of measurement standards, these factors are not discussed in this section.

Current lethality criteria relate the effects of wounds to the functioning of the extremities; therefore, the analyses of a soldier's ability to carry out his mission are based primarily on the use of the extremities. However, direct wounds of some vital organ, such as an eye or the heart could be immediately incapacitating for all military situations.

3–3. FRAGMENTS, BULLETS, AND FLECHETTES

The vulnerability of personnel to fragments, bullets, and flechettes (Refs. 1 and 2) has been discussed, thus far, only in relative terms; that is, a soldier in a given situation is either more or less vulnerable than another soldier in a different situation. To discuss personnel vulnerability quantitatively, requires a more concrete expression of what vulnerability is. The expression now used is the conditional probability, given a hit, that the target is incapacitated. This probability is based on the mass, area, shape, and striking velocity of the projectile, because these factors govern the depth, size, and severity of the wound. These factors are evaluated for various tactical situations and elapsed times from wounding to incapacitation, as described earlier. The experimental procedures and the analytical means of quantitatively determining the conditional probability of incapacitation by fragments is given in Ch. 5.

Although natural or man-made cover, such as trees or foxholes, has a definite influence on the actual probability of being hit, it has no bearing on the conditional probability, which assumes a hit. However, any combat clothing (i.e., body armor, helmet) reduces the striking velocity of the projectile, and hence influences the depth of penetration and the conditional probability that the target is incapacitated.

3–4. BLAST

The vulnerability of personnel to blast is dependent primarily upon the magnitude and duration of the peak overpressure and the transient winds (dynamic pressure) which accompany an explosion. Blast effects may be conveniently separated into three phases, designated primary, secondary, and tertiary (Refs. 3 and 4).

The injuries associated with primary blast effects are directly related to the peak overpressure at the shock front. The arrival of the shock front is accompanied by a sudden increase in pressure which may produce considerable damage to the human body by crushing, damage to the central nervous system, heart failure due to direct disturbance of the heart, suffocation caused by lung hemorrhage, damage to the gastro-intestinal tract, or ruptured eardrums. In general, damage is most definite in those body regions with the greatest variation in tissue density and, particularly, in the air-containing organs of the body. Use of cover such as foxholes may not have much effect as a protective measure because the reflected shock waves usually magnify the overpressure and, hence, the damage.

Secondary blast effects are those caused by the impact of penetrating and nonpenetrating missiles which are propagated by the transient winds. The effects depend on the missile velocity, mass, size, shape, composition, and density, and on the specific regions and tissues of the body involved. The lethality criteria associated with this type of penetrating missile are the same as those encountered with fragments, bullets, and flechettes. Nonpenetrating missiles impacted against the chest can cause early fatality by bilateral lung lesions very similar to those caused by primary blast. Skull fracture, concussion, rupture and hemorrhage of the liver and spleen, and skeletal fracture can

result, as can crushing injuries from heavy masses of masonry and other building materials

The use of armor and protective equipment serve a purpose against secondary blast effects by reducing the velocity of the missiles, thus lowering the probability of damage.

Tertiary blast effects are defined as damage which is a consequence of physical displacement of the target by the shock wave and the transient winds. Damage from displacement can be of two general types. One type involves the separation of a limb or other appendage from the body. The other type results from a total displacement of the body, with the injury usually occurring during the decelerative phase of the translation. These injuries are comparable to those resulting from automobile and aircraft accidents. The extent of the damage depends upon the portions of the body subjected to accelerative and decelerative loads, the magnitude of the loads, and the ability of the body to withstand these loads. In the case of nuclear explosions, the hazards of violent impact are of considerable importance, because of the great range and long duration of the blast winds.

Miscellaneous effects of blast can involve exposure to ground shock, dust, temperature phenomena, contact with hot dust and debris, and conflagration heat from blast-produced fires.

The nature of damage from ground shock concerns injuries from displacement, and impact with heavy objects, as noted above. A sufficiently high concentration of dust, under certain circumstances, has proved fatal simply through deposits in, and obstruction of, the small airways of the lungs. The danger depends upon time of exposure and the concentration of appropriately sized dust particles. Thermal injuries involve burns from thermal radiation and other sources (Par. 3–5).

When considering damage resulting from blast, it is not the rule, nor is it practical, to consider the injuries on the basis of only one of the three phases. Injuries from explosions, nuclear explosions in particular, are caused by a combination of all the blast damage mechanisms. An example of combined blast injury may be quoted directly from the report on the Texas City explosion (Ref. 5).

"A man, age thirty-nine, had just come from loading one of the ships and was standing on the pier facing the ship. When the explosion occurred, he was blown into the sky so high that he could see over a warehouse and then he was blown laterally into the water. He did not lose consciousness and was able to swim to land. The injuries sustained were perforation of both eardrums, severe scalp lacerations, severe lacerations of left upper arm with extensive infection, left ulnar (forearm) paralysis, and laceration of the right foot." All three damage phases were involved in this accident. The perforation of the eardrums resulted from the primary blast effects, and a combination of secondary and tertiary effects caused the lacerations and paralysis.

3–5. FIRE AND THERMAL RADIATION

The vulnerability of personnel to fire and thermal radiation probably can be described best in terms of their effects, as flame and flash burns, respectively. The two types of burns can usually be distinguished by the characteristic-profile nature of the flash burns as compared with overall burning by flame burns. Usually flash burns will be limited to small areas of the body not covered by shielding, such as clothing. Flame burns, on the other hand, will cover large areas of the body, because the clothing will catch on fire.

The severity of flash burns will range from mild erythema (reddening) to charring of the outermost layers of the skin, with the severity being determined by the thermal energy received and the rate at which the energy is delivered. With flash burns, there is no accumulation of fluid under the skin, as there is with flame burns. In addition, the depth of penetration is considerably less than that associated with injuries caused by direct flames.

The degree and type of cover that the individual affords himself will for the most part determine the amount of burns resulting from thermal radiation. Cover, however will not have much effect in reducing flame burns if the

combustible material around the individual is burning.

When fire or thermal radiation are the products of bombs, the incapacitating effects of any burns sustained will be magnified because many of the medical facilities will be either damaged or destroyed. As a result, medical attention will not be available.

3–6. BIOLOGICAL AND CHEMICAL AGENTS

Biological and chemical warfare agents are designed primarily as anti-personnel agents. Biological warfare is the military use of living organisms, or their toxic products, to cause death, disability (either temporary or permanent), or damage to man, his animals, or his crops. Chemical warfare is the military use of toxic gases, liquids, or solids to produce casualties (Refs. 6 and 7).

Biological warfare agents are selected to produce many results, from brief but crippling disease to widespread serious illness resulting in many deaths, depending on the effects desired. Chemical warfare agents cause incapacitation by choking, blood poisoning, destruction of the nervous system, shock, vomiting, and various other effects.

Due to the seriousness of the effects, and because these agents are designed primarily for use against personnel, it is sufficient to say that personnel are vulnerable, and that the effects depend upon the particular agent, the concentration, and the duration of exposure. Any undisciplined group, particularly without protective gear such as masks, would be especially vulnerable to casualties and to panic, with complete demoralization resulting as a secondary effect.

3–7. NUCLEAR RADIATION

Most effects of nuclear radiation on living organisms depend not only on the total dose absorbed, but also on the rate of absorption, and the region and extent of the body exposed. However, a few radiation phenomena, such as genetic effects, apparently depend only upon the total dose received and are independent of the rate of delivery. In other words, the damage caused to the reproductive cells by radiation is cumulative. In the majority of instances the rate of delivery is the important factor; that is, biological effect of a given total dose of radiation decreases as the rate of exposure decreases. For instance, if the whole body were exposed, 800 roentgens in a single dose would have a high probability of being fatal, but it would not cause death or have any noticeable clinical effects if supplied evenly over a period of 25 to 30 years.

Different portions of the body show different sensitivities to radiation, although there are undoubtedly variations of degree among individuals. In general, the most radio-sensitive parts include the lymphoid tissue, bone marrow, spleen, organs of reproduction, and gastrointestinal tract. Of intermediate sensitivity are the skin, lungs, kidney, and liver; whereas muscle and full-grown bones are the least sensitive. Those parts that are the most radio-sensitive are not able to replace the damaged cells, or the rate of replacement is so slow that the functional ability is impaired.

Although a large dose (450 roentgens or greater) will generally be fatal if administered over the whole body, the same dose received in a small area may result in considerable damage to that area, but the overall health of the individual may not be seriously affected. One of the reasons for this difference is that when the exposure is restricted, the unexposed regions can contribute to the recovery of the injured area. The effects of cover will, therefore, influence the amount of exposure, and thus the number of incapacitations.

Section II (U)—Ground Vehicles

3–8. INTRODUCTION

Ground vehicles are vulnerable to a variety of kill mechanisms, with the most effective kill mechanism depending on the type of vehicle. A customary method of classing vehicles is according to armor protection, as armored vehicles or unarmored vehicles. The presence or absence of armor on a vehicle does not in it-

self determine the function or battlefield role of the vehicle. For example, a cargo-carrying vehicle, wheeled or tracked, armored or unarmored, has logistic support as its role.

In general, ground vehicles are vulnerable in varying degrees to shell fragments and armor-piercing projectiles, blast, fire, thermal and nuclear radiation, shaped charges, electronic jamming of communications equipment, and to any of these or other kill mechanisms which can affect the crew. Vulnerability to fragments and projectiles depends on the type, amount, and obliquity of the armor (if any), and on the mass, shape, and striking velocity of the impacting projectile or fragment.

In any vehicle vulnerability assessment the crew must be considered as a factor. The crew of a soft (unarmored) vehicle, unlike an aircraft or armored vehicle crew, are not normally considered to be a vulnerable part of the vehicle, because replacements should be available from the other parts of the vehicle convoy. On the other hand, it might be possible to immobilize an armored vehicle simply by incapacitating the crew.

Nuclear weapon effects include: initiation of fires and destruction of protective coatings by thermal radiation; crushing of external equipment, and overturning by blast; and radiation damage to organic compounds, optical elements and electronic components. Vulnerability is usually related to weapon yield, distance from detonation, type of burst, and environmental and terrain conditions.

Tank tracks and running gear, and light vehicles with their cargo and crew, are vulnerable to conventional high explosive blast. Shaped charges can provide penetration of heavy armor and cause damage, by the residual jet and back spall, to internal components such as fuel, ammunition, engine, crew, steering controls, and fire control equipment. Armored vehicles (as well as others) are also vulnerable to other specialized high explosive weapons such as plastic charges, which, when detonated on the outer surface of the armor, cause severe spalling of the inner surface. The spalling produces large numbers of high velocity fragments, damaging to crew and internal components.

3–9. ARMORED VEHICLES (Ref. 8)

3–9.1. General

Armored vehicles can be divided into two basic groups: those meant to participate in the assault phases of offensive combat, the armored fighting vehicle (AFV); and those intended to participate in offensive combat, but not ordinarily in the assault, of which type the armored infantry vehicle (AIV) and the armored self-propelled artillery piece (AAV) are examples. Assault, in this context of offensive combat, is the final step in the attack during which the objective is physically overrun and taken.

The relative amount of armor protection of the AFV, as compared to the AIV and armored artillery vehicle (AAV), is a distinguishing feature because the AFV is the only vehicle specifically designed to defeat armor-piercing projectiles and shaped charges.

The AIV represents a class of armored, tracked vehicles which is adaptable to a wide variety of uses on the battlefield. A few examples are armored personnel carriers, mortar carriers, ambulances, and command post vehicles. Increased mobility and limited protection to the infantry are provided by the armored personnel carrier type of AIV, and to artillery weapons and crews in the case of the AAV (Refs. 9 and 10).

3–9.2. Armored Fighting Vehicles (Ref. 11)

The AFV is typified by the tank, which combines the favorable assault characteristics of great firepower, mobility, shock action, and armor protection. In the normal combat situation destruction of the AFV is not required, some degree of incapacitating damage usually being sufficient.

As a reference basis, certain damage categories have been established for the AFV. "M" damage will cause complete or partial immobilization of the vehicle. "F" damage causes complete or partial loss of the ability of the vehicle to fire its main armament and machine guns.

"K" damage will cause the vehicle to be destroyed (Ref. 12). These levels of damage, considered to be levels of functional impairment, are described fully in Ch. 6.

The vulnerability of an AFV is usually thought of in terms of its resistance to perforation by armor-piercing projectiles, shell fragments, and shaped charges, and by its structural resistance to blast from nuclear detonations or HE projectiles. In actuality, the vehicle or its internal components may be damaged to some degree by mechanisms which will not ordinarily destroy or cripple the vehicle.

For example, bullet splash from small arms projectiles may enter small, exposed openings and clearances. (Bullet splash is defined as the dispersion of finely divided or melted metal which is produced upon the impact of a projectile on armor plate or other hard objects). The splash particles have been known to enter openings and make two or three right-angle turns before losing enough energy to be nonlethal. The air grilles of engine compartments are normally susceptible to the passage of splash, because they are designed to allow the entrance of sufficient air to cool the engine. The clearance around a gun shield is still another location where splash may enter.

When the AFV is attacked with projectiles of various calibers, it is possible for movable components to become wedged, burred, or deformed in such a manner that their usefulness is impaired. This is termed immobilization of the part (as contrasted with immobilization of the complete vehicle). Movable components include such items as hatch covers, gun shields, complete tank turrets, and the main gun tube.

High explosive blast (or nuclear blast) damage may be incurred in AFV armor structure, especially where the blast effect is confined. The impacting wave front will cause the armor plate to act like a flexible membrane so that it vibrates back and forth like a drumhead. This same phenomenon may also be induced by the impact of armor-piercing projectiles. The resulting high- and low-frequency vibrations of the structure impose a shock, which is a sudden change in the motion of the system that varies with the magnitude and duration of the forces imposed. Even in those cases where the armor structure itself can resist the shock, interior components fastened to the armor structure may be severely damaged. Some of these components may even become detached and act as secondary missiles. Traversing mechanisms, control and instrument panels, sighting systems, radios, turret bearings, and turret traversing gear rings are all important components that are apt to be damaged by shock (Ref. 13).

The armor distribution of the AFV is based upon resistance to ground attack, consequently the vehicle is more vulnerable to air attack. Overhead armor protection (turret top, hull top, engine grilles) is usually considerably less than that found on the front and sides. Air attack can include strafing fire from small arms, small caliber guns (20 mm, and U. S. S. R. 23 mm and 37 mm cannons), rockets, and aerial bombs. Actual test data pertaining to the vulnerability of various components of armored vehicles, and suggested means for reducing their vulnerability, are to be found in Refs. 13 and 14.

A successful means of attack upon the AFV is usually not found in some ideal weapon or kill mechanism, but rather in the proper tactical use of many available devices which will exploit the weaknesses of the AFV. Some of these weaknesses are its considerable weight, exposed suspension and weapons, and poor vision when buttoned-up.

Tactical defensive positions will be protected against the AFV by mine fields capable of damaging or destroying vehicles by blast, shaped charges, Napalm (buried), or any combination of these. As hostile tanks approach the position, small arms (bullets) and artillery fire (blast and fragments) employed against the tanks will force the tank crews to button-up and will hamper the vehicle commanders (by an impairment of vision) in controlling the movement of the vehicles. Armor-piercing and incendiary bullets, together with shell fragments, will damage some vision mechanisms, and make the tanks more vulnerable to anti-tank weapons. While buttoned-up, the ve-

hicles are more likely to veer into mine fields, where many vehicles will at least become "M" damaged. Many of those tanks not immobilized by mines will be made so by direct blast effect from HE shells against the vehicle suspension system. Once the vehicle is a stationary target, it is more likely to be hit by direct-fire anti-tank weapons, where an "F" or "K" kill can be more easily accomplished. In addition, the stowed ammunition and fuel in the vehicle provide a source of destructive energy which can be ignited, thereby damaging the vehicle.

3-9.3. Armored Infantry and Armored Artillery Vehicles

The AIV and the AAV are provided with limited armor protection, consistent with their weight limitations and tactical roles. Such armor is resistant (at some given range) to small arms fire of caliber .50 or less, high explosive shell fragments, and blast (up to a certain size shell as specified for the vehicle). The AIV and AAV are generally vulnerable to any anti-tank weapon. This includes such devices as small caliber anti-tank weapons which fire AP projectiles (U. S. S. R. 14.5 mm, for example), the smallest shaped charges currently used by infantry troops, and almost any anti-vehicle land mine.

The function of these vehicles does not require that they seek anti-tank weapons; rather, they attempt to avoid them. For example, an armored artillery vehicle does not normally encounter enemy gun positions; therefore, its armor is based upon providing protection only against shell fragments and some HE blast from counter-battery fire. Nor is the armored infantry vehicle intended to assault hostile gun positions. The armored infantry advance as far as possible in their personnel carriers, dismounting when forced to by enemy fire or when making the final assault upon the objective. The vehicular weapons of the personnel carriers, either mounted or dismounted, may then be used to support the attack from appropriate positions (Refs. 9 and 10). The AIV thus provides support but avoids direct fire upon itself, because it is protected only by thin armor.

3-10. UNARMORED VEHICLES

The category of unarmored vehicles includes two basic types: those transport-type vehicles (trucks, tractors, jeeps, etc.) which have logistical support of combat forces as their primary mission; and unarmored wheeled or tracked vehicles serving as weapons carriers. Unarmored vehicles are often referred to as "soft" vehicles.

An unarmored vehicle is not only vulnerable to all the kill mechanisms which can be used against armored vehicles, but also is vulnerable to most anti-personnel weapons (small-caliber ball ammunition, anti-personnel mines, many shell fragments which cannot perforate light armor, HE blast, etc.). A quantitative measure of minimum-damage vulnerability for such a vehicle is to consider it a casualty if a part necessary for its operation is damaged to a degree which causes the vehicle to stop within a specified time limit. Although most of the presented area of such a target, at some given aspect, may be perforated by projectiles or fragments without their striking a component required for operation, some of the components essential to operation (electrical, fuel, lubricating, and cooling system) are especially vulnerable to impacting objects. These components are considered to be the parts most likely to fail under attack.

Section III (C)—Ground Structures

3-11. (U) INTRODUCTION

An accurate knowledge of the response of structures and structural components to the various mechanisms of attack is of vital interest to the structural designer, military planner, and those agencies concerned with military and civil defense. The nature of target loading and response, and the parameters governing this response, are required to establish design and damage criteria and, hence, the vulnerability of the structure to a specific damage mechanism.

The effects of each of the possible damage mechanisms are produced by different means. Therefore, any study associated with a particular class of structure must be conducted with respect to a particular damage mechanism. When a target is exposed to a weapon which produces several damage mechanisms, such as those produced by a nuclear weapon, the possible synergistic effects are ignored because the problem becomes too complicated. Only the mechanism most effective against the particular target is employed in the vulnerability analysis.

Although structures are vulnerable to the great majority of kill mechanisms, only air blast, ground shock, and fire will be considered in the discussion of vulnerability which follows. These phenomena are considered as the most probable mechanisms which will completely destroy or severely damage the structure. Both surface and subsurface structures will be considered in the discussion.

With respect to air blast, the loading, in magnitude and duration, and the deflection and elasticity of the target element are the prime variables affecting the degree of damage. The target size and composition influence the loading transmitted to the structure, by making it primarily either more susceptible to diffraction loading or to the drag forces produced by the dynamic pressures. Surface structures are usually most vulnerable to air blast.

Ground shock is primarily effective against structures located underground. The intensity of the shock wave, the type of soil formation, and the flexibility of the structure are most significant in determining the degree of damage.

Structural fires are usually a secondary result of some other damage mechanism. (For nuclear weapons, primary thermal radiation may produce the fires.) Nevertheless, in many cases, the fire will spread sufficiently to cause severe damage well outside the lethal radius of the primary effect. The vulnerability of a structure to fire is largely dependent upon the combustibility of the building and its contents.

Detailed information concerning the vulnerability of ground structures to the above mentioned damage mechanisms is presented in the following pages. Additional information on target response may be found in Ch. 7, Par. 7–17. Data related to target vulnerability analysis and computation of damage probabilities is found in Ch. 7, Par. 7–20.

3–12. (C) SURFACE STRUCTURES

3–12.1. (C) Air Blast

3–12.1.1. (C) *Loading*

a. (U) *General*

The loading on an object exposed to air blast is a combination of the forces exerted by the overpressure and the dynamic pressure of the incident blast wave. The loading at any point on a surface of a structure can be described as the sum of the dynamic pressure, multiplied by a local drag coefficient, and the overpressure after any initial reflections have cleared the structure. Since the loading changes rapidly during the time the blast wave is reflecting from the front surfaces and diffracting around the structure, loading generally comprises two distinct phases. They are: loading during the initial diffraction phase (Ch. 2, Sec. IV); and loading after the diffraction is complete, or drag loading (Ref. 15).

Air blasts originate from two sources, namely conventional high-explosive weapons and nuclear weapons. The loadings that result from the two sources differ due to the difference in overpressures and duration of the positive phase of the blast wave. Air blasts from conventional high-explosives have relatively short positive phases; therefore, the resulting loadings are more important during the diffraction phase. The considerably longer positive phases of the blast waves of nuclear explosions make the resulting loadings significant during both the diffraction and drag phases. Figure 3–1 shows the effects of the nuclear bomb explosion at Nagasaki.

b. (C) *Loading During the Diffraction Phase*

(U) A large closed structure with walls that remain intact throughout most of the load duration is primarily sensitive during the diffraction phase, since most of the translational load is applied during this period. As the blast wave strikes this type of structure, it is reflected, creating overpressures greater than those inci-

Official U. S. Army Photograph

Figure 3–1. Area Around Ground Zero at Nagasaki, Before and After the Atomic Explosion

dent thereon. Subsequently, the reflected overpressure decays to that of the blast wave. As the blast wave progresses, it diffracts around the structure, eventually exerting overpressures on all sides. Before the blast wave reaches the rear face, overpressures on the front exert translational forces in the direction of blast wave propagation. After the blast wave reaches the rear face, the overpressures on the rear tend to counter the overpressures on the front. For smaller structures, the blast wave reaches the rear face more quickly, so that the pressure differential exists for a shorter time. Thus, the net translational loading resulting from overpressures during the diffraction phase depends primarily on structural dimensions. For some structures where wall failure takes place early in the diffraction phase, only the structural frame may remain, and essentially no load is transmitted to the structural frame during the remainder of the diffraction process. A longer duration blast wave does not materially change the magnitude of the net translational loading during the diffraction phase, or the resulting damage. In other words, the structure is primarily sensitive to the peak blast wave overpressure. Table 3–1 lists those types of structures which are generally affected primarily by blast wave overpressure during the diffraction phase (Ref. 15).

c. (C) ***Loading During the Drag Phase***

(U) During the diffraction phase, and until the blast wave has passed, dynamic pressures are also exerted on structures. Dynamic pressure loading is commonly referred to as drag loading. In the case of a large, closed structure the drag phase loading is small relative to the overpressure loading during the diffraction phase. For smaller structures, the drag phase assumes greater relative importance. For small area components such as the frame of a structure after removal of siding, the translational load applied as a result of the drag phase is much greater than the net translational loading from overpressures during the diffraction phase. For frame buildings with siding removed during the diffraction phase, the drag phase is the predominant factor in producing further damage. Likewise, for bridges the net load during the diffraction phase is applied for an extremely short time, but the drag phase continues until the entire blast wave passes the structure. Because the drag phase duration is closely related to the duration of the blast wave overpressure, rather than to the overall dimensions of the structure, damage is dependent not only on peak dynamic pressure but also on the duration of the positive phase of the blast wave. Thus, damage to this type of structure is dependent on weapon yield as well as peak target loading.

(U) Table 3–2 lists those types of structures which are sensitive primarily during the drag phase. Some elements of a structure may be damaged more by loading during the diffraction phase, other elements of the same structure may be damaged more by the drag phase. The dimensions and orientation of a structure. together with the number and area of the openings and the rapidity with which wall and roof

TABLE 3-1 (C). DAMAGE TO TYPES OF STRUCTURES PRIMARILY AFFECTED BY BLAST-WAVE OVERPRESSURE DURING THE DIFFRACTION PHASE (U)

Description of Structure	Description of Damage		
	Severe	Moderate	Light
Multistory reinforced concrete building with reinforced concrete walls, blast resistant designed, no windows, three story.	Walls shattered, severe frame distortion, incipient collapse of first floor columns.	Walls cracked, building slightly distorted, entranceways damaged, doors blown in or jammed. Some spalling of concrete.	
Multistory reinforced concrete building, with concrete walls, small window area, five story.	Walls shattered, severe frame distortion, incipient collapse of first floor columns.	Exterior walls badly cracked. Interior partitions badly cracked or blown down. Structural frame permanently distorted; spalling of concrete.	Windows and doors blown in. Interior partitions cracked.
Multistory wall-bearing building, brick apartment house type, up to three stories.	Bearing walls collapse, resulting in total collapse of structure.	Exterior walls badly cracked, interior partitions badly cracked or blown down.	Windows and doors blown in. Interior partitions cracked.
Multistory wall-bearing building, monumental type, four story.	Bearing walls collapse, resulting in collapse of structure supported by these walls. Some bearing walls may be shielded enough by intervening walls, so part of structure may receive only moderate damage.	Exterior walls facing blast badly cracked, interior partitions badly cracked, although toward far end of building damage may be reduced.	Windows and doors blown in. Interior partitions cracked.
Wood frame building, house type, one or two stories.	Frame shattered so that structure is for the most part collapsed.	Wall framing cracked. Roof badly damaged. Interior partitions blown down.	Windows and doors blown in. Interior partitions cracked.
Oil tanks, 30 feet in height, 50 feet in diameter. (Tanks considered full; more vulnerable if empty.)	Large distortion of sides, seams split, so that most of contents are lost.	Roof collapsed, sides above liquid buckled, some distortion below liquid level.	Roof badly damaged.

panels fail, determine which type of loading is predominant in causing damage.

3-12.1.2. (U) Response (Refs. 17, 18 and 19)

Structural characteristics determining response and damage are ultimate strength, period of vibration, ductility, dimensions, and mass. Ductility increases the ability of a structure to absorb energy, and increases its resistance to failure. Brittle structures, such as those of masonry construction, have little ductility and fail after relatively small deflections. Ductile structures, such as steel frame buildings, have the ability to withstand large and even permanent deflections without failures (Ref. 4). For each representative structural type listed in Tables 3-1 and 3-2, structural characteristics are similar enough that structures of a given type are considered to respond to approximately the same degree, under identical loading conditions, despite a recognized variability of unknown amount for each type.

The direction of the imposed load may have considerable effect on response. Most structures are able to withstand much larger verti-

cal than horizontal loads. Consequently, they are more resistant to a load imposed on the top of a structure than to an equal load imposed against a side. Thus, in the early regular-reflection region, damage from the same peak loading is likely to be less than damage to a similar structure in the Mach reflection region (Ch. 4, Sec. I).

TABLE 3–2 (C). DAMAGE TO TYPES OF STRUCTURES PRIMARILY AFFECTED BY DYNAMIC PRESSURES DURING THE DRAG PHASE (U)

Description of Structure	Description of Damage		
	Severe	Moderate	Light
Light steel frame industrial building, single story, with up to 5-ton crane capacity. Light-weight, low-strength walls fail quickly.	Severe distortion of frame (one-half column height deflection).	Some distortion of frame; cranes, if any, not operable until repairs made.	Windows and doors blown in. Light siding ripped off.
Heavy steel frame industrial building, single story, with 50-ton crane capacity. Light-weight, low-strength walls fail quickly.	Severe distortion of frame (one-half column height deflection).	Some distortion of frame; cranes, if any, not operable until repairs made.	Windows and doors blown in. Light siding ripped off.
Multistory steel frame office type building, five story. Light-weight, low-strength walls fail quickly.	Severe frame distortion. Incipient collapse of lower floor columns.	Frame distorted moderately. Interior partitions blown down.	Windows and doors blown in. Light siding ripped off. Interior partitions cracked.
Multistory reinforced concrete frame office type building, five story. Light-weight, low-strength walls fail quickly.	Severe frame distortion. Incipient collapse of lower floor columns.	Frame distorted moderately. Interior partitions blown down. Some spalling of concrete.	Windows and doors blown in. Light siding ripped off. Interior partitions cracked.
Highway and railroad truss bridges, spans of 150 feet to 250 feet.	Total failure of lateral bracing, collapse of bridge.	Some failure of lateral bracing such that bridge capacity is reduced about 50 per cent.	Capacity of bridge unchanged. Slight distortion of some bridge components.
Highway and railroad truss bridges, spans of 250 feet to 550 feet.	Total failure of lateral bracing, collapse of bridge.	Some failure of lateral bracing such that bridge capacity is reduced about 50 per cent.	Capacity of bridge unchanged. Slight distortion of some bridge components.
Floating bridges, U. S. Army standard M–2 and M–4, random orientation.	All anchorages torn loose, connections between treadways or balk and floats twisted and torn loose, many floats sunk.	Many bridle lines broken, bridge shifted on abutments, some connections between treadways or balk and floats torn loose.	Some bridle lines broken, bridge capacity unimpaired.
Earth covered light steel arch with 3-foot minimum cover (10-gauge corrugated steel with 20–25 foot span).	Total collapse of arch section.	Slight permanent deformation of arch.	Deformation of end walls, possible entrance door damage.
Earth covered light reinforced concrete structures with 3-foot minimum cover (2 to 3 inch panels with beams on 4-foot centers).	Total collapse.	Deformation, severe cracking and spalling of panels.	Cracking of panels, entrance door damage.

In the case of earth-covered surface structures, the earth mounding reduces the reflection factor and improves the aerodynamic shape of the structure. This results in a large reduction in both horizontal and vertical translational forces. It is estimated that the peak force applied to the structural elements is reduced by a factor of at least 2 by the addition of earth cover. The structure is somewhat stiffened against large deflections by the buttressing action of the soil, when the building is sufficiently flexible.

Air blast is also the determining factor in the damage to surface structures resulting from relatively shallow underground bursts. However, the distances from weapon burst to target, for a given degree of damage, are reduced from those for a surface burst.

3–12.1.3. (C) Classification of Damage

a. Basis of Classification

A major factor to consider in assessing structural damage is the effect of the damage on continued operations within the structure. If rugged equipment is mounted on a foundation at ground level, major distortion or even collapse of a structure may not preclude operation of the equipment. Conversely, if the equipment is tied in with the structural frame, distortion of the structure may prevent or seriously affect operability. No satisfactory general method has been developed for relating damage of structures to the damage to operational equipment contained in the structures. This relationship may be established for particular cases of interest on an individual basis. In general, severe structural damage approaching collapse entails a major reduction in operating capability.

b. Conventional Bomb Damage Classification

Due to the differences between conventional and nuclear bombs, their damage classifications are different. Since the effects of conventional bombs are usually local on a large structure, or around the point of burst, there are two damage classifications: "structural"; and "superficial." The damage descriptions of these two classes are similar to the last two classes for nuclear explosions, as indicated below. In the case where the structure is small, the structural classification for conventional bombs may extend into the first class listed below.

c. Nuclear Bomb Damage Classification

There are three damage classifications for nuclear explosions, described in following subparagraphs. A more detailed description of the application of these classifications to specific targets is given in Tables 3–1 and 3–2 (Ref. 16).

(1) Severe Damage

That degree of structural damage which precludes further use of a structure for the purpose for which it is intended, without essentially complete reconstruction. Requires extensive repair effort before being usable for any purpose.

(2) Moderate Damage

That degree of structural damage to principal load carrying members (trusses, columns, beams, and load carrying walls) that precludes effective use of a structure for the purpose for which it is intended, until major repairs are made.

(3) Light Damage

That degree of damage which results in broken windows, slight damage to roofing and siding, blowing down of light interior partitions, and slight cracking of curtain walls in buildings, and as described in Tables 3–1 and 3–2 for other structures.

3–12.2. (U) Ground Shock

Ground shock has to be so intense in order to cause serious damage to foundations of surface structures that the damage area for these structures is confined closely to the crater area of a surface or underground burst. Since the air blast at these ranges will be most devastating, the ground shock damage is neglected.

3–12.3. (U) Fire

The vulnerability of a structure to fire is dependent upon many factors. Some of these factors are: the combustibility of the building and its contents; the existance and adequacy of fire-stop partitions, etc; the weather conditions; etc.

Fires caused by high-explosive and nuclear bombs are for the most part, except possibly in the case of high-megaton yield nuclear weapons, due to secondary blast effects. The majority of such fires are caused by the breaking open or upsetting of tanks, drums, pipes, ovens or furnaces containing hot or highly inflammable materials, or by electrical short circuits.

In the case of the nuclear bomb, damage also may result from thermal radiation. Primary thermal radiation is seldom a factor in damage to structures. However, since exterior and interior surfaces of many structures are covered with protective coatings (paint), these coverings may be scorched at moderate levels of thermal radiation from the fireball. All structures, whether principally of steel and concrete construction, or of wood, contain some combustible material, and it is likely that some kind of kindling fuels will be present. Therefore, the possibility must always be considered that fire may be initiated in kindling fuels and spread to other components.

Certain classes of surface structures, such as badly weathered or rotted wooden buildings, buildings with thatched roofs, houses with lacquered paper windows, etc., may be ignited by direct thermal radiation, with resultant self-sustaining fires (Ref. 15).

3–13. (C) UNDERGROUND STRUCTURES

3–13.1. Air Blast

Air blast is the controlling factor for damage to lightweight soil-covered structures and shallow-buried underground structures. The soil cover provides surface structures with substantial protection against air blast and also with some protection against missiles.

Light-weight shallow-buried underground structures are those constructed deep enough for the top of the soil cover to be flush with the original grade. However, they are not sufficiently deep for the ratio of span to depth-of-burial to be large enough for any benefit to be derived from soil arching. For depths of cover up to about 10 feet in most soils, there is little attenuation of the air blast pressure applied to the top surface of a shallow-buried underground structure. Also, there is apparently no increase in pressure exerted on the structure due to ground shock reflection at the interface between the soil and the top of the structure.

Soil-covered structures are those that have a mound of soil over the portion of the structure that is above normal ground level. The soil mound reduces the blast reflection factor and improves the aerodynamic shape of the structure. This results in a considerable reduction in the applied translational forces. An additional benefit of the soil cover is the stiffening of the structure, or the additional inertia, that the soil provides by its buttressing action.

The lateral pressures exerted on vertical faces of a buried structure have been found to be about 15 per cent of the pressures on the roof in dry, silty soil. This lateral pressure is likely to be somewhat higher in general, and may approach 100 per cent in a porous, moisture saturated soil. The pressures exerted on the bottom of a buried structure in which the bottom slab is a structural unit integral with the walls may be as low as 75 per cent of the roof pressure, but may range up to 100 per cent of that pressure.

The damage that might be suffered by a shallow buried structure will depend on a number of variables, including the structural characteristics, the nature of the soil, the depth of burial, and the downward pressure (i.e., the peak overpressure) of the air blast wave (Ref. 15).

3–13.2. Ground Shock

An underground structure can be designed to be practically immune to air blast, but such structures can be damaged or destroyed by cratering or by ground shock due to a near-surface, true-surface, or an underground burst.

The mechanism of damage to underground structures from ground shock and cratering is dependent upon several more or less unrelated variables, such as the size, shape, flexibility, orientation of the structure with respect to the explosion, and the characteristics of the soil or rock.

The criteria for damage caused by cratering and ground shock may be described in terms of three regions, namely:

1. The crater itself.
2. The region extending roughly out to the

limit of the plastic zone (roughly 2½ times the crater radius).

3. The zone in which transient earth movement occurs without measurable permanent deformation.

The shock parameter mainly responsible for damage has not been defined either theoretically or empirically. However, there is considerable evidence that the degrees of damage can be related, without serious error, to the crater radius. Some examples of this type of relationship are given in Table 3–3 (Ref. 16).

For purposes of estimating earth shock damage from surface or subsurface bursts, underground structures are divided into various categories as follows:

1. Relatively small, highly resistant targets in soil. This type, which includes reinforced concrete fortifications, can probably be damaged only by acceleration and displacement of the structure in its entirety.
2. Moderate size, moderately resistant targets. These targets are damaged by soil pressure as well as acceleration and bodily displacement.
3. Long, relatively flexible targets. These include buried pipes and tanks, which are likely to be damaged in regions where large soil strains exist.
4. Orientation sensitive targets. Targets such as gun emplacements may be susceptible to damage from small permanent displacements or tilting.
5. Rock tunnels. Damage to such targets from an external explosion is caused by the tensile reflection of the shock wave from the rock-air interface, except when the crater breaks through into the tunnel. Larger tunnels are more easily damaged than smaller ones. However, no correlation between damage and tunnel size or shape is known.
6. Large underground installations. Such installations can usually be treated as a series of smaller structures.

TABLE 3–3 (C). DAMAGE CRITERIA FOR UNDERGROUND STRUCTURES (U)

Structure	Damage	Damage Distance	Remarks
Relatively small, heavy, well designed underground targets.	Severe	$1\frac{1}{4}R_a$	Collapse.
	Light	$2R_a$	Slight cracking, severance of brittle external connections.
Relatively long, flexible targets, such as buried pipelines, tanks, etc.	Severe	$1\frac{1}{2}R_a$	Deformation and rupture.
	Moderate	$2R_a$	Slight deformation and rupture.
	Light	$2\frac{1}{2}$ to $3R_a$	Failure of connections. (Use higher value for radial orientation of connections.)

Note. R_a=Apparent Crater Radius.

Section IV (S)—Aircraft

3–14. (U) INTRODUCTION

Aircraft vulnerability concerns the many factors which determine the ability of an aircraft to withstand combat damage. In particular, it indicates the means for improving the chances for survival of aircraft in battle and, by inference, indicates weapons which show the greatest promise of inflicting critical damage on an aircraft. Thus, aircraft vulnerability and weapon lethality are closely interrelated subjects of comparable importance; they are the defensive and offensive aspects of the same phenomena. It is the expressed desire of the procuring agencies for manned military aircraft to incorporate the principle of minimum vulnerability in new design concepts, within the limitations of the overall design requirements.

3–15. (C) BASIC CONSIDERATIONS

3–15.1. (C) Initial Studies of Aircraft Vulnerability

Prior to 1939, consideration of aircraft in terms of target vulnerability and weapon lethal-

ity received little coordinated study. The results of this neglect soon became evident when battle experience was gained, but it was then found that any major design changes needed to reduce the vulnerability of aircraft were not easily introduced into the production line, and were consequently late appearing in service aircraft. Considerable losses were undoubtedly suffered due to the late introduction of such changes.

Shortly after World War II, a firing program (Ref. 20) was initiated at the Ballistic Research Laboratories (BRL), Aberdeen Proving Ground, Maryland, in order to determine the vulnerability of aircraft and their components to various aircraft weapons. This effort, based in part on work by the New Mexico Institute of Mining and Technology, under contract to the Bureau of Ordnance, was supplemented by a progress report (Ref. 21) relating to the two complementary aspects of the so-called "Optimum Caliber Program." The objects of this program were: first, to determine the probability that a single round of existing ammunition striking an airplane would cause a certain level of damage; and, second, to assess the overall effectiveness of complete armament installations, with the object of indicating the answer to the whole problem of what armament should be carried by aircraft to meet various tactical situations. The report of this work represents the beginning of a considerable amount of literature available on the subject of aircraft vulnerability and, in particular, the subject of aircraft "terminal vulnerability."

3–15.2. (C) Vulnerability Definitions

(U) The word "vulnerability," as it appears in the literature, has two common usages. Vulnerability in the overall or "attrition sense" is the susceptibility of an item to damage, which includes the considerations of avoiding being hit. Vulnerability in the restricted or "terminal sense," is the susceptibility of an item to damage, assuming that it has been hit by one or several damaging agents. Therefore, the probability of obtaining a kill on an aircraft target is found equal to the probability of obtaining a hit times the probability that the hit results in a kill (Ref. 22). This chapter considers only the latter factor, or the terminal ballistic vulnerability of aircraft.

(C) The chance of survival of an aircraft in battle is influenced by many factors, including its flight performance and maneuverability, its defensive armament and offensive equipment, and the skill and morale of its crew. The term aircraft vulnerability, however, is restricted in meaning. It is commonly used to refer to the extent to which an aircraft is likely to suffer certain specified categories of damage, when the weapon used to attack it either strikes the aircraft or bursts in some desired zone around it.

3–15.3. (C) Vulnerability Factors

The major factors which influence the chance of survival of an aircraft are in most instances the inherent safety (or invulnerability) of the airframe and components, which together make up the basic aircraft, and the efficiency of any protective devices with which it may be fitted. Evidence on these factors can usually be obtained by experiment. When this evidence is related to an attack of a specified nature and from a specified direction, it forms the usual basis of aircraft vulnerability assessments. The vulnerability of components such as the power plants can be assessed separately in a similar manner, and can be included in an overall assessment. Care must be exercised in making the overall assessment, however, because the individual damage effect may be quite different from the overall effects. For example, in the case of a single-seated aircraft, 100 per cent probability of lethal injury to the pilot will give a similar probability for the loss of the system; whereas, damage which is 100 per cent lethal to one engine of a four-engine aircraft may not be lethal to the entire aircraft. These individual components are usually referred to as singly and multiply vulnerable, which terms are discussed in Ch. 8, Par. 8–22.

It is useful at this point to define two terms which are used in the collection and analysis of aircraft target vulnerability (Ch. 8, Par. 8–22). Presented Area: the area of the projection of the configuration of a given component

upon a plane perpendicular to the line of flight of the attacking projectile or warhead. Vulnerable Area: the product of the presented area and the conditional probability of a kill for a random hit on the presented area. (It is assumed that all projectiles approach the presented area on parallel paths.)

3–15.4. (C) Use of the Empirical Approach

A synthesis of the vulnerability characteristics of aircraft targets is based mainly on empirical relationships for the vulnerability of the major aircraft components. A large part of these data are obtained from firings against aircraft conducted at the various proving grounds. These include firings of selected weights of bare and cased charges about, in contact with, and within aircraft structures, filled fuel tanks, and both reciprocating and jet engines; also the firing against all major aircraft components by various projectiles. Damage caused in field firings against aircraft is assessed by qualified military or civilian personnel (sometimes in conjunction with the manufacturer), who prepare a detail description of the damage in addition to numerical estimates for the various damage categories.

This empirical approach is subject to strong economic and humane restrictions and limitations; as a result, the test aircraft is usually on the ground with no personnel aboard. (The effects of altitude and aerodynamic and inertial forces on the airframe are usually estimated.) Firing trials may be made against stressed structural members, against engines running under cruising conditions, or against canopies which are subject to realistic conditions of temperature and pressure. In-flight vulnerability investigations are naturally difficult to stage, but are sometimes essential. An example is the investigation of the probability of causing fires in the fuel systems, at altitudes which demand conditions of air temperature, air density, and high-speed air flow not easily reproduced simultaneously on the ground. An additional limitation on this empirical approach is that the sample sizes obtained are usually small, restrictions on the sample size being especially stringent for the more recent aircraft.

The test aircraft may then be considered as collections of components, rather than as entities in themselves. Since the "aircraft of the future" that are under study are composed of structures, fuel cells, or engines physically similar to corresponding components in the test aircraft, the information obtained can be applied directly in some cases, with due correction for changes in areas and physical arrangements.

3–15.5. (C) Damage Categories

In order to classify damage effects, several kill or damage categories are in common use, as follows:

- KK The aircraft disintegrates immediately after being hit (in addition, denotes complete defeat of its attack).
- K The aircraft falls out of control immediately, without any reasonable doubt (usually specified as 1/2 minute, or less).
- A The aircraft falls out of control within 5 minutes.
- B The aircraft will fail to return to its base. This is commonly taken as being 1 hour away for a jet, or 2 hours away for a piston-type engine aircraft.
- C The aircraft does not complete its mission after being hit.
- E The aircraft could complete its mission after being hit, but is damaged to the extent of not being able to go on the next scheduled mission (usually denotes a bad crash on landing).

It is important to note that in order to assess B or C damage, it is necessary to define the mission on which the aircraft is engaged. Frequently in the literature, the K and KK categories are grouped as sub-categories under the A-damage assessment. In addition, reference is sometimes made to an R-damage category, which is "detectable by radar facilities." For the most part, damage is usually assessed in the K, A, and C categories.

3–15.6. (C) Damage Assessment

In tests on aircraft vulnerability, a basic method of determining the degree of damage is by assessment. After a test aircraft is damaged, assessors are asked to estimate the probability that the damage produced would incapacitate the aircraft to a specified degree (damage category) assuming a certain mission, crew reaction, etc. Thus, an assessment of 0, 0, 0, 0 may be given for A, B, C, and E categories, respectively, meaning that the damage would not cause a crash within 2 hours, would not interfere with the mission, and would not cause a crash on landing. An assessment of 0, 100, 0, 0 means that the assessors believe that the damage would cause a crash within 2 hours, although not within 5 minutes. For example, such an assessment may be made for damage causing oil loss to the engine of a single piston-engine aircraft. To enable the assessors to express their uncertainty as to the outcome of damage, intermediate numbers between 0 and 100 are used. Thus, a 20A assessment means that the assessor is inclined to believe that the damage would not result in a crash within 5 minutes, although he is not sure of this. Wherever possible, independent assessments of the same damage are obtained from two or more assessors. Detailed descriptions of the conduct of the field trials and of the assessment procedure are provided in the many BRL reports dealing with analyses of firing data. (A and B assessments, made for damage to the engine of a multi-engined aircraft, refer to the ability of that engine to deliver power, rather than to a crash.)

A comment of interest on the assessment procedures has been made by Arthur Stein, formerly of BRL (Ref. 20).

"It will be noted that the numbers used to describe the various categories of damage are described as probabilities often written as percentages. Strictly speaking, however, this is not correct, since the particular damage suffered by the aircraft will generally either cause a crash or it will not in the stated interval of time, assuming a set of standard conditions under which the aircraft is operating. The numerical assessment, therefore, chiefly represents the uncertainty of the assessor as to whether the damage would result in a kill or not. If the individual assessment is 20A, for example, the assessment is in error by 20 per cent or 80 per cent, since the damage would actually have produced a kill or no kill within 5 minutes. If assessments are not biased, however, the expected value of many such assessments on various parts of the plane would be the correct value and in the 'long run' one would arrive at a correct value for the vulnerability of the plane. The parameters of the error distribution can be estimated if one has a large number of cases in which the same damage has been assessed independently by different assessors. Such information would also yield information as to the assessibility of various aircraft components."

It must be strongly emphasized that assessment represents the basic measure of aircraft terminal vulnerability.

3–15.7. (C) Categories of Associated Data

3–15.7.1. (C) *Modes of Damage*

There are numerous modes of damage which can effect aircraft kills. Some of these are given in the following list:

1. The detonation of the aircraft bomb load.
2. The killing of a sufficient number of essential crew members.
3. The ignition of a lethal fire.
4. The killing of a sufficient number of engines.
5. Lethal damage to the airframe.
6. Lethal damage to the armament system.

3–15.7.2. (C) *Typical C-Damage Factors*

The word lethal, as used in the above paragraph, implies that only a specified category of kill results, and does not imply any fixed degree of damage severity. It should also be noted that the determination of what constitutes a kill, in a given situation, can often require the use of simplifying assumptions for a feasible analysis procedure. For example, listed below are some of the factors to be considered in a typical C damage situation:

1. Aircraft position along the flight profile at the time damage occurs.

2. The assigned mission of the particular aircraft.
3. The crew (number, skill, individual specialties, and determination to complete the mission).
4. Item(s) damaged.
5. Alternate equipment available.
6. Type and intensity of enemy action.

3–15.7.3. (U) *Significant Aircraft Components*

In determining aircraft vulnerability, the aircraft may be defined by the sum of the following components, which in turn include subcomponents:

1. Airframe.
   a. Structure (Fig. 3–2).
   b. Controls (flight).
2. Fuel system.
3. Power plant.
4. Personnel (only crew necessary for mission).
5. Armament system.
   a. Guns.
   b. Bombs.
   c. Fire control.
   d. Bomb sight.
   e. Radar.
6. Miscellaneous (tires, flaps, etc.).

3–15.7.4. (C) *Damaging Agents*

The many different types of damaging agents in use against aircraft can be placed under three basic categories of armament:

1. External blast weapons.
   a. Conventional rounds.
   b. Nuclear rounds (including thermal and nuclear radiation).
2. Direct contact weapons.
   a. Bullets: armor-piercing (AP) and armor-piercing incendiaries (API).
   b. Shells: high explosives (HE) and high-explosive incendiaries (HEI).
   c. Fragments: shaped charges, rods, etc.
3. Fragmentation/blast weapons (controlled fragmentation burst combined with a high explosive charge).

3–15.7.5. (C) *Relative Vulnerability of Components*

Although no such listing can be correct in all cases, Table 3–4 affords a general idea of the terminal vulnerability of the various components to the several (non-nuclear) damaging agents (Refs. 23 and 24).

3–16. (S) AIRCRAFT BY TYPE AND LOCATION

3–16.1. (U) General

The vulnerability of an aircraft target as an entity (in contrast to the test aircraft which were considered as collections of components) depends upon the location and type of aircraft target. Normally the aircraft is in flight, but when parked it may become a ground target. Aircraft may be further defined by two general types, combat and non-combat, with various

TABLE 3–4 (C). RELATIVE VULNERABILITY OF AIRCRAFT COMPONENTS (U)

	Personnel	Fuel System	Power Plant		Airframe	Armament & Misc.
			Turbojet	Piston		
Incendiary bullets	High	Uncertain	Moderate	Low	Negligible	High
HE & HEI shells	High	Uncertain	High	High	Varies	High
Fragments & non-incendiary bullets	High	Uncertain	Moderate	Low	Negligible	Moderate
Rods	High	Uncertain	High	High	High	High
External blast	Negligible	Negligible	Negligible	Negligible	Moderate to high	Moderate

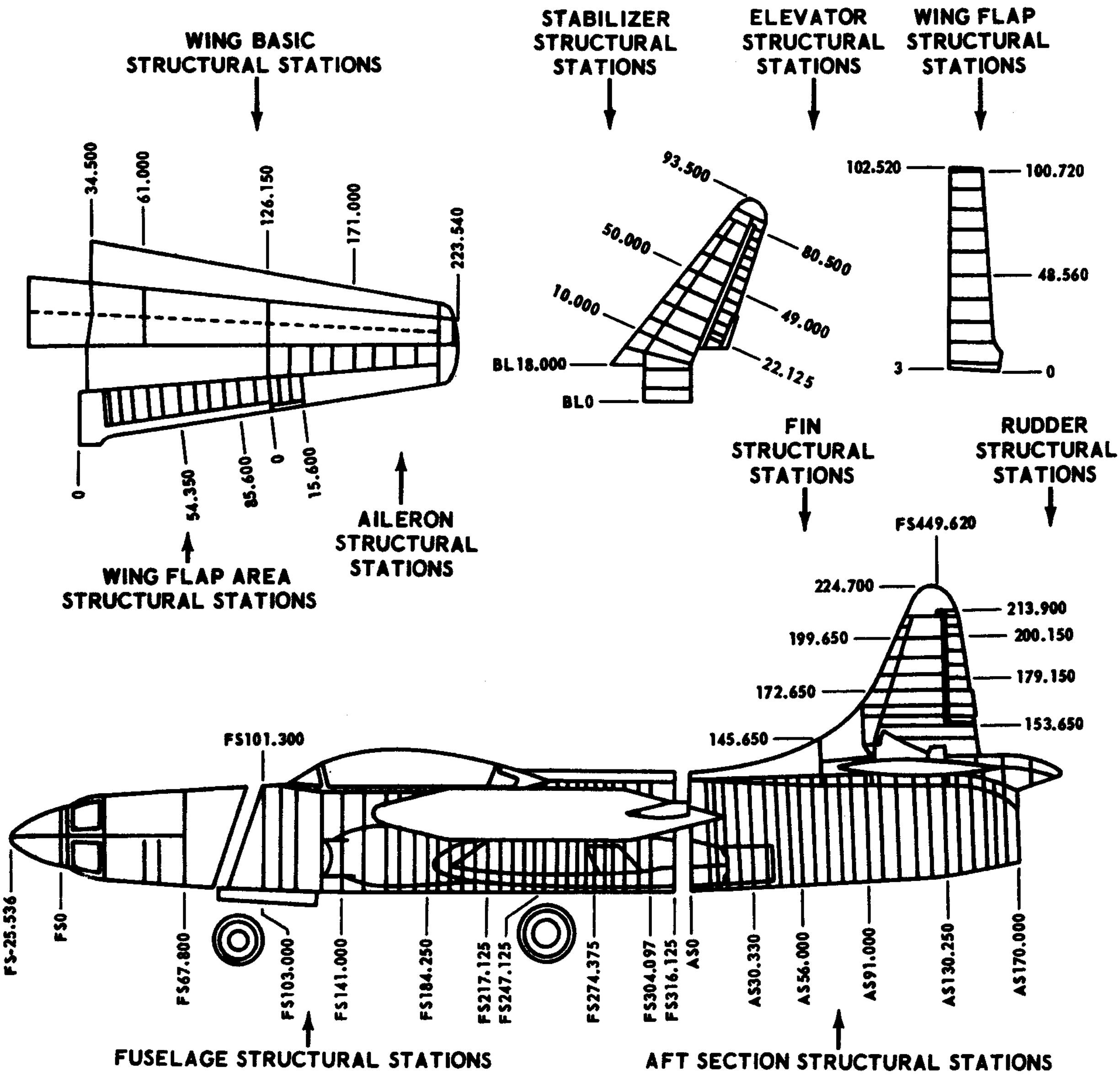

Figure 3–2 (C). Stations Diagram, F94C Aircraft (U)

classes of aircraft falling into these two categories according to their mission or function. A corollary grouping is in terms of the fixed-wing, the rotary-wing (helicopter), the new STOL (short takeoff and landing), and new VTOL (vertical take off and landing) types of aircraft.

3–16.2. (S) Aircraft in Flight

3–16.2.1. (S) *Combat Aircraft*

(U) Combat aircraft are generally classed as bomber, fighter, or attack aircraft, depending primarily on the mission of the aircraft, and to a lesser degree on the design configuration. World War II aircraft were characterized within these classes by size, weight, and speed; but the character of later day aircraft are such that these characteristics are not as obvious. An excellent source of physical data on the characteristics of aircraft is *Jane's All the World's Aircraft* (Ref. 25).

(S) The greatest combat risk to a bomber force during the past few years has been from fighters armed either with 20- to 40-mm cannon

or with small (2- to 3-inch) unguided rockets; the attacks being almost wholly from the rear or off by small angles. The projectiles have usually been impact-fused explosive or explosive/incendiary types.

(S) An aircraft is likely to suffer severe structural damage if hit by a small rocket; and with either cannon or rocket there will be a high probability of damage to fuel systems and power plant, with a corresponding chance of delayed kill.

(S) With the 2- to 3-inch rocket, the structural and mechanical damage (internal blast) from a hit is likely to be so great that the possible additional effects due to fire need scarcely be considered. Incendiary effects from the small, gun-fired shell could be very severe, and would depend largely on the type of fuel system used.

(S) Both surface-to-air and air-to-air guided missiles are now available in addition to the conventional fighter weapons just mentioned. If the guided missile warheads are of the large, blast type, structural damage can result. For the fragmenting type warheads, there will be a large increase in the vulnerability of the pilots of the bomber, a high probability of leakage from fuel tanks, damage of radar equipment, and possibly a high fire risk, due to the high-velocity fragmentation given by the warhead.

(S) The main combat hazards to the fighter have been the attack from ahead by bomber return fire, and the attack from the rear by enemy fighters. Missiles in either case have been explosive shells from aircraft cannon, or small rockets. Hits against high performance jet fighters are likely to cause severe structural damage, engine failure, or pilot injury. Even superficial damage at the time of hit can result in a lethal situation, subsequently, due to a high-g maneuver such as LABS (Low Altitude Bombing System). Owing to the rapid changes in altitude by the fighter during combat, there may be difficulty in maintaining an inert atmosphere (purging) above the fuel in the tanks, and unless new methods are employed there will be a risk of fuel tank explosion and fire. The introduction of guided missile warheads with blast and fragmentation effects now produce the possibility of structural damage to the fighter by external blast, in addition to increasing pilot vulnerability and the risk of fire due to high velocity fragments.

(S) The main risk to attack aircraft has been from ground or ship weapons (mainly conventional guns and rockets) firing impact fuzed explosive projectiles of up to about 3 inches, and from small arms fire with either armor-piercing or incendiary bullets. The damage effects will be generally similar to those described for the fighter aircraft, but the emphasis will be mainly on attacks from the front hemisphere. Wartime evidence has indicated the importance, to aircraft engaged on ground-attack missions, of self-sealing protection for fuel tanks and armor protection for pilots and items such as oil coo'ers. The value of such equipment is, however, a subject of great debate. Small surface-to-air missile weapons presently in development will create an additional threat to attack aircraft at low altitudes.

(C) It is possible during the time of war to obtain a fair indication of the vulnerability characteristics of military aircraft, and the frequency and effects of different types of combat damage, by making detailed investigations of air casualties in action. From this evidence, it is possible to determine the main causes of enemy and friendly losses in air warfare, and the relative vulnerability of the various parts of each aircraft.

(S) Evidence of the causes of aircraft losses in World War II was gathered by the British Operational Research Sections attached to the Royal Air Force and the United States Army Air Force (Ref. 26). For example, it was found that the Bomber Command's losses in night operations during the latter part of the war were caused approximately as follows:

1. 75 per cent by fighter attack.
2. 20 per cent by antiaircraft gunfire.
3. 5 per cent by accidents, including navigational errors, collisions, fuel shortage, engine failure, etc.

Of these bomber losses due to enemy action, by far the greatest number either resulted from fire or suffered fire as a secondary effect.

(S) From the best evidence available, it is estimated that the significantly vulnerable parts of the bomber are:

1. Engines (piston type)—by mechanical damage and fire.
2. Fuel systems—by fire, internal explosion, or loss of fuel.
3. Flight control systems and surfaces—by mechanical damage from multiple hits causing break-up and loss of control.
4. Hydraulic and electrical services—mainly by fire.
5. Bombs and pyrotechnic stores—by explosion or fire.
6. Pilots—by incapacitation (an infrequent cause of loss).

(S) For the single-engined fighter types, the order of vulnerability due specifically to light anti-aircraft fire from the ground was estimated to be:

1. Engine—by mechanical damage and fire.
2. Pilot—by injury or death.
3. Fuel system—by loss of fuel or fire.

Although fire is not stated as the major risk, because the damage would generally cause loss whether combined with fire or not, a substantial proportion of the losses was undoubtedly accompanied by fire. In air-to-air engagements, the single-engined fighter was believed to be most frequently destroyed by the cumulative effects of multiple hits on the structure and main flight control surfaces.

(S) Information from air operations in the Korean war has been small as regards evidence on causes of losses in combat. This appears to be due to the small percentage of actual losses caused by enemy action, and to the overwhelming emphasis on ground-attack sorties by the air forces of the United Nations. However, there is some evidence, obtained by the United States Air Force, from which the following facts appear to emerge. Based on combat hours of duty, and for the same type of ground-attack mission, the single-engined jet aircraft receives only about 50 per cent as many hits from anti-aircraft projectiles (bullets or small shells) as the single-engined piston aircraft. This difference in the number of hits appears to be related to the different tactics employed during the dive and pullout. For example, the jet aircraft attacks at a much higher speed and thus spends far less time than the piston aircraft at altitudes subjected to accurate gunfire. When hit, the piston aircraft is 50 per cent more likely to be lost than the jet aircraft. A large proportion of the vulnerability of the piston aircraft can be attributed to the vulnerability of its engine oil coolers. These observations relate only to the particular conditions and particular types of attacking projectiles (now possibly outdated) which were encountered by the United Nations' forces in Korea.

(S) The actual vulnerability of any potentially vulnerable part of an aircraft depends to a great extent on its area of presentation. For example, a medium-range, four-engined bomber with gross weight of about 120,000 pounds may have an average presented area of 1,500 square feet. The average areas of some of the potentially vulnerable components might be approximately as follows:

1. Structure (including fuel tanks)—1,200 square feet (80%).
2. Fuel with tanks at ⅔ capacity—340 square feet (23%).
3. Pressure Cabin—130 square feet (9%).
4. Power plants—90 square feet (6%).
5. Pilot—7 square feet (½%).

It will be seen that the structure is by far the largest of the potentially vulnerable items, while the fuel tanks, pressure cabin, and power plants also present relatively large areas. For the long range bomber of the near future, the fuel may have a considerably larger presented area than the value just quoted.

(C) Aircraft in flight are relatively vulnerable to the blast and thermal effects of nuclear detonations. Since aircraft are designed within narrow limits for flight and landing loads, the structure can withstand only small additional loads imposed by weapon effects. Blast overpressure, on striking an aircraft surface, may cause dishing of panels and buckling of stiffeners and stringers. On the side struck by the blast wave the pressure is increased, above the incident intensity, by reflection, and a diffractive force of short duration is generated. As the wings, empennage, and fuselage are completely enveloped by the blast, further dishing and buckling of skins and structure

may result from the crushing effect of the differential pressure between the outside and inside of the aircraft components. Additional damaging loads are also developed by the particle velocity accompanying the blast wave. The particle velocity results in drag loading in the direction of the wave propagation (usually termed "gust loading" with reference to aircraft). The duration of the gust loading is many times that of the diffractive loading, and it develops bending, shear, and torsion stresses in the airfoil and fuselage structures. These are usually the major stresses on an aircraft in flight.

(C) The weapon thermal energy which is absorbed by aircraft components can also produce damaging effects. Very thin skins are rapidly heated to damaging temperatures by exposure to the short-period thermal flux, because the energy is absorbed by the skin so much more rapidly than it can be dissipated by conduction and convective cooling. Exposed fabric, rubber, and similar materials with low ignition and charring temperatures, are vulnerable items which may also initiate extensive fire damage at even very low levels of radiant exposure. In recent years, designers of military aircraft have reduced aircraft vulnerability to thermal effects by coating thin-skinned materials with low absorptivity paints, by eliminating ignitable materials from exposed surfaces, and by substitution of thicker skins for very thin skins. With these protective measures and design modifications, aircraft can be safely exposed at radiant exposure levels several times those which formerly caused serious damage.

3–16.2.2 (U) *Non-combat Aircraft*

Non-combat aircraft include the following types: cargo, transport, utility, and observation and reconnaissance. The latter two types are often converted combat aircraft. These aircraft are characterized by their function, size, and speed, and by the type of their construction, which is a conventional, World-War-II type of design. This is a semi-monocoque fuselage and full cantilever wings with a stressed aluminum skin. The collection of terminal ballistic vulnerability data for this type of aircraft has received little specialized attention in the past. However, because most of the testing on combat aircraft has been with targets reflecting this type of construction, there is in fact considerable information available for those who may be interested.

3–16.2.3. (C) *Rotary Wing and Other Aircraft*

(U) It is necessary to distinguish rotary-wing (helicopter) aircraft from conventional fixed-wing aircraft, and also the new STOL and VTOL vehicles. The vulnerability of rotary-wing aircraft is similar in many respects to the fixed-wing aircraft, but the following items may not be similar and require individual attention:

1. Relative location of fuel, and personnel.
2. Complex control system.
3. Rotor drive system and gear boxes.
4. Main and tail rotor blades.
5. Unconventional airframe (slender tail cone, etc.).

(C) Firing tests have been conducted at the Wright Air Development Center (WADC) against rotor blades, using caliber .30 and caliber .50 projectiles. The blades were fired on so as to obtain damage to the structural or spar portion of the blade and then whirl-tested to determine the effects of damage. The damage caused by these projectiles was found not to be serious. This agrees with Korean combat results, which show that small caliber holes in portions of the blades are not serious. However, a perforation by a larger projectile, such as a 37-mm AP or HE projectile, could cause the loss of a blade, which would be most serious.

(C) The problem of the vulnerability of low flying aircraft in the forward area has recently been given higher priority by the Army, due to new tactics and organizations developed by the Army, new reconnaissance drones and aircraft being developed by the Signal Corps, and new STOL and VTOL vehicles being studied for air transport by the Transportation Corps. Because of the missile threat at medium and high altitudes, most Army air tactics envision low flying aircraft. In the region below 500 feet, light arms (40-mm AA, and smaller caliber) will be a threat to these aircraft in forward areas. In the near future, small surface-to-air weapons

now in development may be included. Vulnerability testing for these special-purpose aircraft has been initiated.

3–16.3. (C) Parked Aircraft

(U) Considerable interest has been shown in the vulnerability of parked aircraft in the vicinity of a nuclear air blast. Nuclear weapon tests have included parked aircraft placed at various locations and orientations with respect to the burst point.

(C) The diffraction phase loading and the drag phase loading have varying relative importance in producing damage to parked aircraft. In general, the diffraction phase is of primary importance in the zones of light and moderate damage. In the zone of severe damage, the drag phase assumes more importance. Orientation of the aircraft with respect to the point of burst affects vulnerability considerably. With the nose of the aircraft directed toward the burst, higher weapon-effects inputs can be absorbed without damage than for any other orientation. The longer duration of the positive phase of the blast from a large yield weapon may result in some increase in damage over that expected from small yields at the same overpressure level. This increase is likely to be significant at input levels producing severe damage, but is not likely to be important at the levels of moderate and light damage. Experiments have shown that revetments provide only slight shielding against blast overpressure, and under some conditions reflected pressures within the revetment are higher than corresponding incident pressures. Revetments do provide significant shielding from damage due to flying debris born by the blast wave.

(C) Aircraft properly prepared with reflective paint, and with all vulnerable materials shielded from direct thermal radiation, will not be damaged by thermal inputs at distances where damage from blast inputs is not severe. Aircraft not so prepared may sustain serious damage at very low thermal levels, as a result of ignition of items such as fabric-covered control surfaces, rubber and fabric seals, cushions, and headrest covers. Aircraft painted with dark paint are especially vulnerable to thermal radiation damage, because the dark painted surfaces absorb three-to-four times the thermal energy that is absorbed by polished aluminum surfaces or surfaces protected with reflective paint. Temporary emergency shielding such as that provided by trees, buildings, embankments, or similar barriers may be useful for thermal protection of unprepared aircraft, but any of these may increase the blast damage by adding to the flying debris or by multiple reflection of incident overpressures.

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3–17. REFERENCES

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Chapter 4 (S)

COLLECTION AND ANALYSIS OF DATA CONCERNING KILL MECHANISMS

Section I (S)—Blast

4–1. (U) INTRODUCTION

4–1.1. Scope of the Section

This section covers the collection and analysis of data involving blast waves as a kill mechanism. Separate paragraphs discuss both quantitatively and qualitatively the various parameters associated with air, surface, and subsurface blasts from conventional high explosives (chemical explosives) and nuclear explosions. In additional paragraphs are discussed the effects of mechanical factors on blast, and methods of blast instrumentation. In general, the bulk of the material will apply to blast waves produced by either conventional or nuclear explosions. In certain areas, however, the discussion will emphasize the particular features of the blast wave produced by nuclear explosions.

4–1.2. Comparison of Conventional and Nuclear Explosions

The primary differences between the conventional (HE) explosion and a nuclear explosion (setting aside from the present subject the radiation effects) is that the energy from nuclear explosions is developed in a much smaller space, and the temperatures developed are approximately 10,000 times higher. As a result, there is an almost instantaneous release of energy in the nuclear explosion. Consequently, the nuclear explosion may be considered more nearly a point source of energy, permitting simplified analytical solutions to the equations of motion.

Other differences between conventional and nuclear explosions concern blast pressures and energy yield. The pressure at small distances from ground zero is higher for nuclear than for conventional explosions; but at large distances the reverse is true. The much greater energy yield of a nuclear explosion makes a qualitative difference in the effects. For instance, the duration of the blast produced by an atomic bomb is longer than the characteristic vibration periods of most structures which can be destroyed. Therefore, the criterion for estimating the damage to structures by nuclear bombs is usually the peak overpressure or the peak drag pressure, rather than the impulse, which is the commonly used criterion for HE bombs.

4–1.3. Cross-Reference Information

The general discussion of the mechanisms of blast and ground shock in Ch. 2, Secs. IV and V, respectively, should be read for introductory purposes. In Ch. 3, each of the various sections includes information on the vulnerability of specific types of targets to blast phenomena. Reference should be made to each of the chapters of Part Two for information on the collection and analysis of blast data as applied to specific types of targets.

4–2. (S) AIR BURST

4–2.1. (U) Introduction

Most of the damage resulting from a high explosive or nuclear explosion air burst is due, either directly or indirectly, to the blast wave (shock wave) which accompanies the explosion. Most structures will suffer some degree of damage when subjected to pressures in excess of the standard atmospheric pressure (overpressure). The distance from the point of detonation to which damaging overpressures

will extend is dependent on the energy yield of the weapon and the height of burst. In considering the destructive effect of a blast wave, it is important to study, in some detail, the various phenomena associated with the passage of the wave through the atmosphere.

4–2.2. (U) Description of the Blast Wave

4–2.2.1. Overpressure

The expansion of the intensely hot gases at high pressure causes a blast wave to form and move outward at high velocity. The pressures in this wave are highest at the moving front and fall off toward the interior region of the explosion. In the very early stages of the blast wave movement, the pressure variation with distance from the point of detonation is somewhat as illustrated in Fig. 4–1.

As the blast wave travels in the air away from its source, the overpressure at the front steadily decreases, and the pressure behind the front falls off in a regular manner. After a short time, the pressure behind the front drops below the surrounding atmospheric pressure and the negative phase of the blast wave is formed. The variation of overpressure is shown in Fig. 4–2 for six successive instants of time, indicated by the numbers t_1, t_2, t_3, etc.

During the negative overpressure (rarefaction, or suction) phase, a partial vacuum is produced and the air is sucked in instead of being pushed away. This means that during the positive (compression) phase, the winds flow away from the explosion; but in the negative phase, the direction is reversed and the winds flow toward the explosion. However, the peak values of the negative overpressure are usually small compared to the overpressures generated during the positive phase. At the end of the negative phase, the pressure has essentially returned to ambient conditions (Ref. 1).

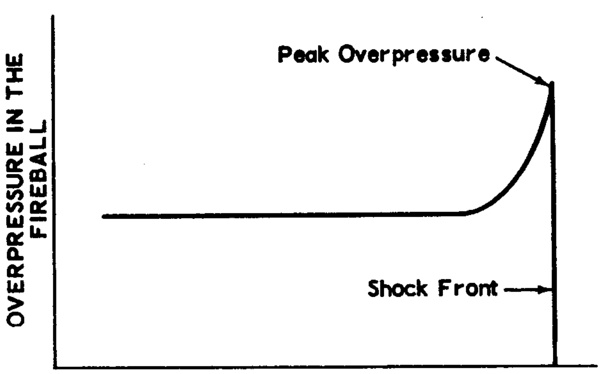


Figure 4–1. Overpressure vs Distance, Early Stages of Blast Wave

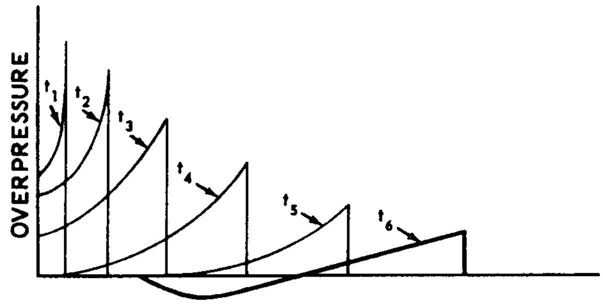


Figure 4–2. Variation of Overpressure With Time

Fig. 4-3 illustrates how overpressure varies with time at a given point. The corresponding general effects to be expected on a light structure, a tree, and a small animal are indicated. For a short interval after detonation there is no increase in pressure because the blast front (shock front) has not yet reached the target. When the shock front arrives, the pressure suddenly increases to a large maximum (the peak overpressure), and a strong wind commences to blow away from the explosion. The velocity of the wind decreases rapidly with time; therefore, it is generally referred to as a transient wind. Following the arrival of the shock front, the pressure falls rapidly, and shortly returns to the ambient condition. At this point, although the overpressure is zero, the wind still continues in the same direction for a short time. The interval from the arrival of the shock front to the return to ambient pressure is roughly one-half second to one second for a 20-kiloton (KT) explosion, and two to four seconds for a 1-megaton (MT) explosion. It is during this period that most of the destructive action of the air burst is experienced.

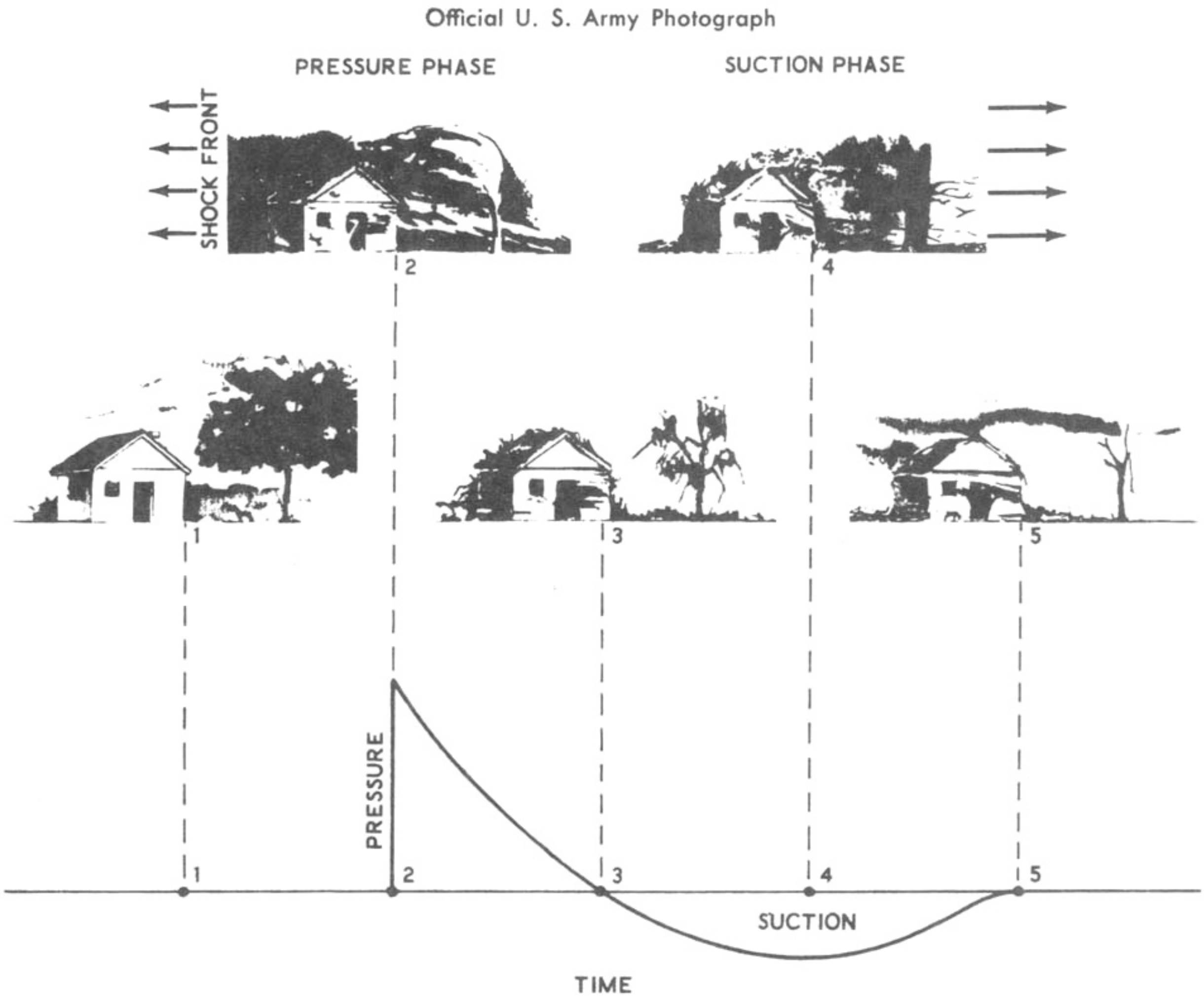


Figure 4–3. Variation of Blast Wave With Time, at a Given Point, and Corresponding Effect of Blast Wave Passing Over a Structure

As the pressure of the blast wave continues to decrease, it drops below ambient pressure, and the suction phase begins. This phase may last for several seconds, and for most of that time the transient winds blow inward toward the explosion. The damage during this phase is generally minor in nature because the peak negative overpressure is small in comparison with the maximum positive overpressure.

In striking opposing surfaces or structures, a process known as diffraction occurs, wherein overpressure is considered to be resolved into face-on (reflected) and side-on overpressures. A general discussion of these forces, and of the corresponding translational force, known as diffraction loading, is given in Ch. 2, Sec. IV.

4–2.2.2. Dynamic Pressure

Although the destructive effects of the blast wave are often related to values of the peak overpressure, the dynamic pressure may be of equal importance. As a function of the wind (particle) velocity and of the density of the air behind the shock front, dynamic pressure is expressed by the equation

$$q = \tfrac{1}{2}\rho u^2$$

where q represents the dynamic pressure, ρ the air density, and u the wind velocity. For very strong shocks, the peak dynamic pressure is larger than the overpressure, but below 69 psi overpressure at sea level, the dynamic pressure is smaller. The peak dynamic pressure, like

the peak overpressure, decreases with distance from ground zero, although at a different rate.

For a great variety of building types, the degree of blast damage depends largely on the drag force associated with the strong transient winds accompanying the passage of the blast wave. The drag force is influenced by certain characteristics of the structure, such as the shape and size, but is generally dependent upon the peak value of the dynamic pressure and its duration at a given location. (Ch. 2, Sec. IV).

At a given location, the dynamic pressure varies with time in a manner similar to the changes of overpressure, but the rate of decrease behind the shock front is different. Both overpressure and dynamic pressure increase sharply when the shock front reaches the given location, then they decrease. Fig. 4–4 indicates qualitatively how the two pressures vary in the course of the first seconds following the arrival of the shock front. The curves indicate that the overpressure and the dynamic pressure return to ambient (0) conditions at the same time. Actually, due to the inertia of the air, the wind velocity (and, therefore, the dynamic pressure) will drop to zero at a somewhat later time, but the difference is usually not significant for purposes of estimating damage. Table 4–1 gives some indication of the corresponding values of peak overpressures, and peak dynamic pressures, as related to the maximum blast wind velocities in air at sea level.

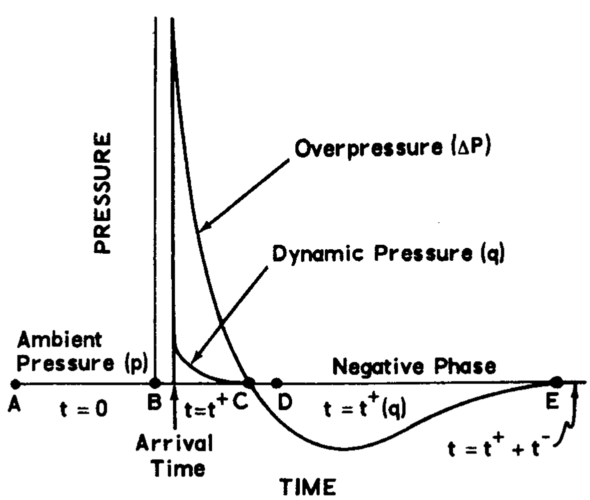


Figure 4–4. Comparison of Variations of Overpressure and Dynamic Pressure vs Time

TABLE 4–1. OVERPRESSURE AND DYNAMIC PRESSURE RELATED TO BLAST WIND VELOCITY IN AIR AT SEA LEVEL

Peak Over-Pressure (psi)	Peak Dynamic Pressure (psi)	Maximum Wind Velocity (mph)
72	80	1,170
50	40	940
30	16	670
20	8	470
10	2	290
5	0.7	160
2	0.1	70

4–2.2.3. *Arrival Time*

As previously stated, there is a finite time interval required for the blast wave to move out from the explosion center to any particular location. This time interval is dependent upon the yield of the explosion and the distance involved. Initially, the velocity of the shock front is quite high, many times the speed of sound, but as the blast wave moves outward its velocity decreases as the shock front weakens. Finally, at long ranges, the blast wave becomes essentially a sound wave and its velocity approaches ambient sound velocity.

4–2.2.4. *Duration*

The duration of the blast wave at a particular location also depends upon the energy of the explosion and the distance from ground zero. The duration of the positive overpressure phase is shortest at close ranges, increasing as the blast wave progresses outward. Because the transient wind velocity behind the shock front decays to zero, and then reverses itself at a time somewhat after the end of the positive overpressure phase, the dynamic pressures may endure longer than the overpressure. However, these elements of the dynamic pressures are so low they are not significant. Therefore, the effective duration of the dynamic pressures may be considered as being essentially the same as the positive phase of the overpressure.

4–2.2.5. *Overpressure and Dynamic Pressure Impulse*

Damage to targets is frequently dependent on duration of the loading as well as the peak

pressure. Parameters related to the duration are the impulses represented in Fig. 4–4, where the overpressure positive phase impulse is the area under the positive portion of the overpressure time curve, and the dynamic pressure impulse is the area under the positive portion of the dynamic pressure time curve.

The overpressure positive phase impulse is represented by the equation

$$I_P = \int_{t=0}^{t=t^+} \Delta P(t)\,dt \qquad (4\text{–}2)$$

in which: $t=0$ is the time of arrival of the shock front; $t=t^+$ is the end of the positive phase; and $\Delta P(t)$ is the overpressure as a function of time.

The positive phase pressure-time curve showing the decay of overpressure at a fixed point in space will vary, depending on the peak overpressure and duration for a given yield at that point. Where overpressures are less than 25 psi, the variation of overpressure with time may be expressed by the following semi-empirical relation:

$$\Delta P(t) = \Delta P\left(1 - \frac{t}{t^+}\right) e^{-t/t^+} \qquad (4\text{–}3)$$

where: $\Delta P(t)$ is the overpressure at any time t; ΔP is the peak overpressure; and t^+ is the positive phase duration.

In a similar manner, the dynamic pressure impulse is represented by the area under the dynamic pressure-time curve, and may be represented by the integral

$$Iq = \int_{t=0}^{t=t_q^+} q(t)\,dt \qquad (4\text{–}4)$$

where: I_q is the dynamic pressure impulse; $q(t)$ the dynamic pressure as a function of time; and t_q^+ the duration of the dynamic pressure positive phase. As with overpressure, the rate of decay varies with peak pressure and duration. Where dynamic pressures are less than 12 psi, the variation of dynamic pressure with time may be represented by the approximate equation

$$q(t) = q(1 - t/t^+)^2\, e^{-2t/t^+} \qquad (4\text{–}5)$$

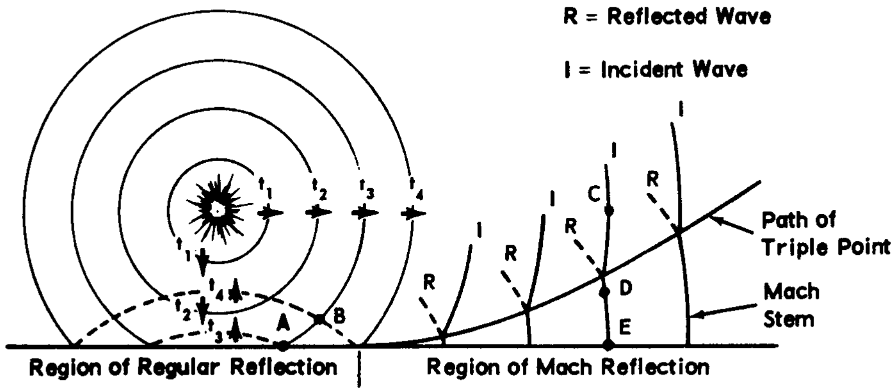
where: $q(t)$ is the dynamic pressure at time t; q is the peak dynamic pressure at the shock front; and t^+ is the overpressure positive phase duration (Ref. 21).

4–2.2.6. *Reflection*

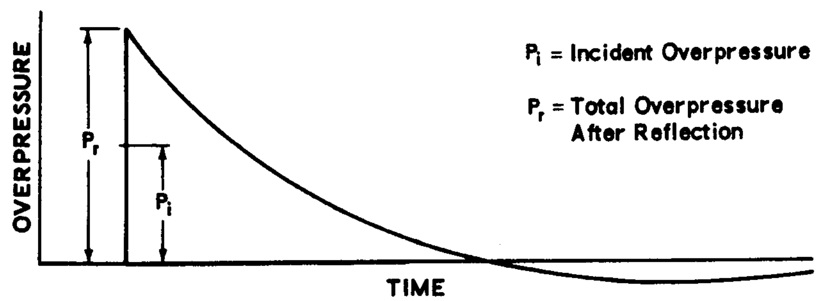
When the incident blast wave from an explosion in air strikes a more dense medium such as the earth's surface, either land or water, it is reflected. The formation of the reflected shock wave in these circumstances is represented in Fig. 4–5(A). This figure shows several stages in the outward motion of the spherical blast originating from an air burst bomb. In the first stage (t_1), the shock front has not reached the ground; the second stage (t_2) is somewhat later in time; and in the third stage (t_3), which is still later, a reflected wave, indicated by the dotted line, has been produced.

When such reflection occurs, an individual or object precisely at the surface will experience a single shock, because the reflected wave is formed instantaneously. Consequently, the value of the overpressure thus experienced at the surface is generally considered to be entirely a reflected pressure. In the region near ground zero, this total reflected overpressure will be more than twice the value of the peak overpressure of the incident blast wave. The exact value of the reflected pressure will depend on the strength of the incident wave and the angle at which it strikes the surface. The variation in overpressure with time, as observed at a point actually on the surface not too far from ground zero, such as point A in Fig. 4–5(A), will be as depicted in Fig. 4–5(B). The point A may be considered as lying within the region of regular reflection; i.e., where the incident (I) and reflected (R) waves do not merge above the surface.

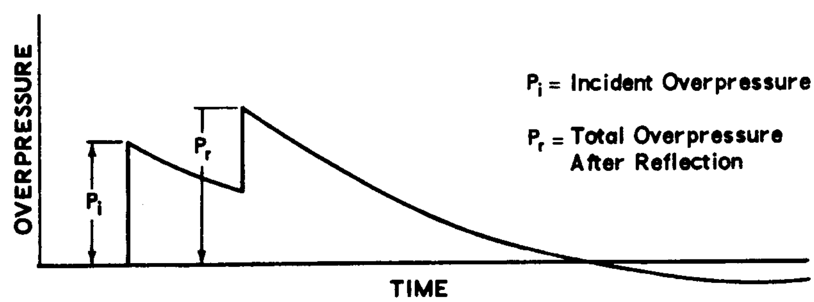
At any location somewhat above the surface, but still within the region of regular reflection, two separate shocks will be felt. The first shock is due to the incident blast wave, and the second, which arrives a short time later, to the reflected wave. Fig. 4–5(C) depicts the variation of overpressure experienced at a location above



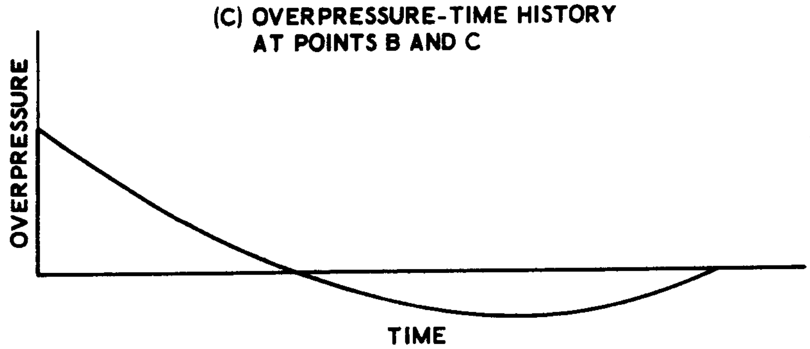
(A) REFLECTION CHARACTERISTICS OF BLAST WAVE NEAR SURFACE



(B) OVERPRESSURE-TIME HISTORY AT POINT A



(C) OVERPRESSURE-TIME HISTORY AT POINTS B AND C



(D) OVERPRESSURE-TIME HISTORY AT POINTS D AND E

Figure 4–5. Reflection of Air-Burst Blast Wave at Earth's Surface

the surface. In determining the effects of air blast on structures in the regular reflection region, allowance must be made for the magnitude and also the directions of motion of both the incident and reflected waves. After passage of the reflected wave, the transient winds near the surface becomes essentially horizontal.

In the early stages of propagation, when the shock front is not far from ground zero, it is reasonable to assume that both the incident and reflected waves travel with velocities that are approximately equal. The reflected wave, however, always travels through air that has been heated and compressed by the passage of the incident wave. As a result, the reflected shock wave moves faster than the incident wave and eventually overtakes it. The two waves then fuse to produce a single shock wave. This process of wave interaction is referred to as Mach or irregular reflection, and the region in which the two waves have merged is called the Mach region. The fusion of the incident and reflected blast waves is indicated schematically in Fig. 4–6, which illustrates a portion of the blast wave profile close to the surface. Fig. 4–6(A) represents a point close to ground zero. In Fig. 4–6(B), a later stage, farther from ground zero, the steeper front of the reflected wave shows that it is traveling faster than the incident wave. At the stage illustrated by Fig. 4–6(C), the reflected shock near the ground has overtaken and fused with the incident shock to form a single shock front, called the Mach stem. The point at which the incident shock, reflected shock, and Mach fronts meet is referred to as the triple point.

As the reflected wave continues to overtake the incident wave, the triple point rises and the height of the Mach stem increases as shown in Fig. 4–5(A). Any object, located either at or above the ground within the Mach region, will experience a single shock whose behavior will follow that of shock fronts in general (the overpressure at a particular location will decrease with time, and the positive phase will be followed by a suction phase). At points in the air above the triple point, a separate shock will be felt from the incident (I) and reflected (R) waves, also as shown in Fig. 4–5(A).

Two aspects of the reflection process are important with regard to the destructive action of the air blast. First, only a single shock is experienced in the region below the triple point (in the Mach region). Second, since the Mach stem is nearly vertical, the accompanying blast wave is traveling in a horizontal direction at the surface, and the transient winds are nearly parallel to the ground. In the Mach region, therefore, the blast forces are applied in a nearly horizontal fashion against above-ground structures and other objects, so that vertical surfaces are loaded more intensely than horizontal surfaces.

The distance from ground zero at which Mach fusion commences is dependent upon the yield of the weapon and the height of burst above the ground. This distance decreases with a decreasing height of burst. Conversely, if the air burst occurs at a sufficiently high altitude, only regular reflection takes place and no Mach stem will be formed (Ref. 1).

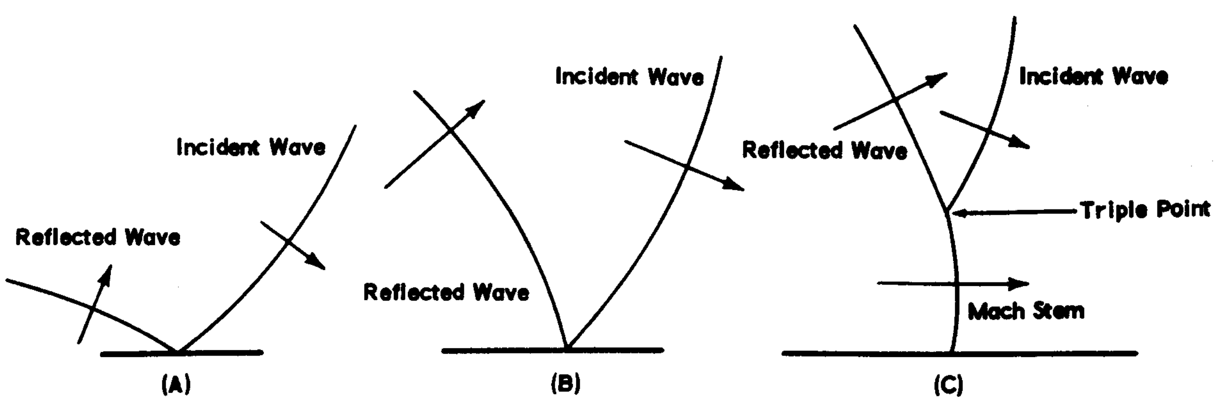


Figure 4–6. Fusion of Incident and Reflected Waves, and Formation of Mach Stem

The problem of reflection is treated more fully in the publications numbered 13 through 17 listed in the Bibliography for this chapter.

4–2.3. (U) Computation of Blast Wave Parameters

4–2.3.1. *General*

The following paragraphs summarize some pertinent aspects of blast wave theory and calculation. Much of the analysis which has been developed in the literature is applicable to either nuclear or high explosive blast. As previously indicated, however, there are certain physical differences which affect the validity of the solutions.

Compared with an ordinary high explosive blast, the energy density of a nuclear explosion is much greater and the corresponding temperatures developed are much higher, by a factor close to 10^4. An HE explosion generates temperatures near 5,000 C degrees; a nuclear explosion results in initial temperatures near 50 million degrees C. The tremendous difference in energy density has several consequences pertinent to the calculational aspects of the problem as well as the physical aspects.

The nuclear explosion can be considered more nearly a point source of energy, and solutions for the resulting blast wave are based on this concept. In an HE explosion the assumption of a finite size energy source is more appropriate, because it takes comparatively longer for the energy to be transferred to the surrounding air. Accordingly, immediately following the HE blast the shock wave pressure is actually less than that predicted from a point source solution. For this reason, much of the more recent literature has been directed toward finite source solutions.

4–2.3.2. *Basic Hydrodynamic Equations*

Before discussing some of the various approaches to the problems of blast wave computations, the basic hydrodynamic equations will be summarized for reference. This discussion is not concerned with equation derivation as such. Only sufficient analysis is given to provide a suitable background. The basic equations of hydrodynamics are equally valid for either a gas or liquid. The associated equations of state are, however, different in each case. The following discussion is based largely on Refs. 2 through 5.

The general problem of fluid flow is to describe what is happening to each region of the fluid as a result of certain outside influences. Frequently, the most significant parameters are the fluid velocity and the fluid pressure, described as functions of position and time. Fluid descriptions in hydrodynamics are based on the concept of a continuum. Roughly speaking, this corresponds to imagining an arbitrarily large number of particles distributed throughout the space of interest, such that each fluid property varies in a continuous manner from particle to particle. In order to adequately describe physical phenomena, however, it will be necessary to permit certain points, lines, or surfaces to exist upon which the fluid properties behave in a discontinuous manner.

The great difficulty of the subject is that, in terms of rigid body mechanics, a system of an infinite number of degrees of freedom has to be dealt with. Stated differently, because continuous variation in properties of the fluid is postulated, each property will be a function of both position and time. Correspondingly, the basic equations of hydrodynamics are partial, rather than ordinary, differential equations.

To make more explicit the above statements, a brief discussion of the two methods for describing fluid motion will be given. The first method, called the Lagrangian description, considers what happens to each individual fluid particle in the course of time. The other method, called the Eulerian description, considers what is happening at each point in space as a function of time. In the latter method, for example, the pressure at a point means the pressure associated with the particle that happens to be passing through that point at that instant. No attempt is made to follow the individual particle.

Consider first the Lagrangian description. Since the motion of each individual particle is to be followed, it will be necessary to identify each particle. This may be done by setting up a coordinate system at a fixed instant of time, say $t = 0$, and by assigning to each particle a set of numbers which may be taken as its co-

ordinate in space. Again for example, when limited to one-dimensional motion, the identifying tag associated with each particle is merely its position on the axis of motion at $t = 0$. As time proceeds, each particle moves, and its position will be a function of time. If x is its location at time t, then $x = x(t)$ for each particle. Let the term a be the initial position of a particle; then a will be different for each particle, and the entire "field" (that is, all particles at the same time) may be described by the single expression

$$x = x(a, t)$$

where, for each particle, a is a fixed number, and t is the time. Correspondingly, the velocity of each particle is given by

$$u = \frac{\partial x}{\partial t}(a, t)$$

where the partial derivative symbol is used to emphasize that a single particle is being considered. For brevity, it is conventional in hydrodynamic literature to write

$$\frac{\partial x}{\partial t}(a, t) = \dot{x}$$

so that

$$\dot{x} = u(a, t) \tag{4-6}$$

In the Euler representation, consider a region of space which may be arbitrarily selected. Again using one-dimensional motion as an example, the location of this region is denoted by a position, x, relative to the coordinate system. Thus, x is an independent variable, and locates a point in space, not a particular particle. Through this space, however, particles pass, and each particle has certain properties associated with it at the instant of passing through the point x. These properties are velocity, acceleration, pressure, density, etc. Accordingly, for example, the velocity at (not of) any point in space is a function of time; for with time, different particles are passing the point. Let the variable which describes all the points in space be x, and let t be the time. Then, the velocity at the point, at that time may be written

$$u = u(x, t). \tag{4-7}$$

At a given instant of time the particular particle passing through the point has this same velocity, by definition. Hence,

$$\dot{x} = u(x, t) \tag{4-8}$$

and if μ has been determined, the position with time of each particle may be determined by integrating Eq. 4–8. The solution will involve a constant of integration, which may be determined by the location of the particle at time $t = 0$. Accordingly, the solution will be expressed in terms of a, the Lagrangian coordinate, written after solution as,

$$x = f(a, t)$$

where f will now be a known functional form. This integration then forms the connection between the Eulerian and Lagrangian technique. It should not be inferred that the physical description just given is easily carried out. In fact, very few solutions are known even in the one-dimensional case.

Referring to Eq. 4–7, an important distinction is made. If each particle that passes the point x has the same characteristics in terms of speed, pressure, etc., as every other particle that passes through the point x, then u, given by Eq. 4–7 does not change with time.

In this case $u = u(x)$ and the flow is said to be steady. It should be noted that the flow, following each particle, may differ from point to point, and still be within this definition of steady. This simple fact illustrates the utility of the Euler description. If, on the other hand, particle properties are different for each succeeding particle that passes through x, then u, at x, is also a function of time, written

$$u = u(x, t).$$

In this case, the flow "field" is said to be *nonsteady*.

4–2.3.3. Basic One-Dimensional Flow Equations

On the basis of the simple introduction, given in the preceding paragraph, some of the basic equations of one-dimensional flow will be summarized. Once again, this discussion is explanatory in nature, and is not concerned with equation derivation as such.

The basic laws governing the behavior of the flow field are the same as those governing any other mechanical system. That is, Newton's laws of motion, conservation of energy, conservation of mass, and the laws of thermodynamics govern.

Consider first the conservation of mass. Using the Euler description, a region in space is selected through which the particles are passing. The rate at which mass leaves the region, minus the rate at which it enters, must equal the rate at which it decreases within the region. If ρ is the mass density, dx the length of the region of cross section A, and u is the entering speed, then ρAu is the mass per unit of time entering the region, and ρAdx is the mass within the region. Using subscripts to denote location,

$$[(\rho u)_{x+dx}-(\rho u)_x]A=-\frac{\partial}{\partial t}(\rho Adx)$$

or

$$\frac{(\rho u)_{x+dx}-(\rho u)_x}{dx}=-\frac{\partial \rho}{\partial t}$$

which, upon passing to the limit, gives the continuity equation for one-dimensional flow. (This assumes that A is a constant.)

Thus,

$$\frac{\partial(\rho u)}{\partial x}+\frac{\partial \rho}{\partial t}=0 \tag{4–9}$$

where $\rho=\rho(x, t)$ and $u=u(x, t)$ are the density and velocity of the particular particle that happens to be passing through the region located at x, at time t.

In a similar manner, by drawing a free body diagram of the region located at x, and by neglecting all forces except pressure, the momentum form of Newton's law is obtained,

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}=-\frac{1}{\rho}\frac{\partial P}{\partial x} \tag{4–10}$$

where P is the static pressure between fluid particles.

Shearing forces are neglected because with such terms the practical problem of solving the blast equations, even in one dimension, is much too difficult; being even too difficult for solution on high speed computers. Fortunately, this assumption of frictionless flow does not invalidate the analysis. Instead, as will be presently discussed, there are regions of the flow in which the viscosity plays a very important part. These regions are the shock waves that show up, mathematically, as discontinuities in the flow. The discontinuities serve as boundaries across which the fluid properties undergo sharp, step changes. It has been found that if the flow field is assumed to be everywhere continuous, frictionless, and adiabatic, except at the discontinuities, a reasonable approximation to the real, physical system can be achieved. In fact, in the sense of a real fluid there are no discontinuities.

Fortunately, however, the rates of change of fluid properties are so great that shock waves may be treated as fluid discontinuities. This permits the neglect of viscosity and heat conduction elsewhere. Even with this simplification, however, straightforward solutions are very difficult, and it is only with the aid of approximation that solutions have been obtained for the one-dimensional, non-steady, blast problem.

The thermodynamic relations required express the first and second of Newton's laws. If E represents the internal energy per unit mass of fluid, which includes thermal and chemical, and $\frac{1}{2}mu^2$ represents the kinetic energy of a particle of mass m, then the first law states that the work done equals the change in total energy (neglecting heat transfer as stated above). Thus, for a particle of dimensions Adx, moving with the speed u, and having density ρ, and pressure P, there is the expression

$$[(Pu)_x-(Pu)_{x+dx}]\,dt\cdot A$$

which is the work done on the particle. Its change in energy is

$$dtAdx\rho\frac{d}{dt}\left[E+\frac{1}{2}u^2\right].$$

Upon passing to the limit, this gives

$$\rho\frac{d}{dt}\left[E+\frac{1}{2}u^2\right]=-\frac{\partial}{\partial x}(P,u)$$

which, by making use of the continuity equation, may be written,

$$\rho\frac{dE}{dt}=\frac{P}{\rho}\frac{d\rho}{dt} \tag{4-11}$$

where $\frac{d}{dt}$ is the total derivative, following the particle. Since each particle is passing through a given location at each instant of time, its properties, ρ for example, may be written

$$\rho=\rho(x,t). \tag{4-12}$$

Then, $\frac{d}{dt}$ of ρ means the total rate of change of ρ with time and position. Hence, using the chain rule of calculus, applied to Eq. 4–12

$$\frac{d\rho}{dt}=\frac{\partial\rho}{\partial t}+\frac{\partial\rho}{\partial x}\frac{dx}{dt}$$

but $\frac{dx}{dt}=u$, the speed, and hence the Lagrangian and Euler derivatives are connected by the relation

$$\frac{d\rho}{dt}=\frac{\partial\rho}{\partial t}+u\frac{\partial\rho}{\partial x} \tag{4-13}$$

where the same expression may be applied to any one of the fluid properties; that is, for velocity itself,

$$\frac{du}{dt}=\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}. \tag{4-14}$$

In these cases it is noted that $\frac{du}{dt}$ means the total rate of change, consisting of a part, $\frac{\partial u}{\partial t}$, caused by changing u at a given point, and of $u\,\frac{\partial u}{\partial x}$, caused by changing location at a given time.

If we assume there are no dissipating processes within the fluid, except at the discontinuities, then the thermodynamic condition of constant entropy may be applied to any region free of boundaries. This leads to the usual adiabatic relation that permits pressure to be expressed as a single-valued function of density alone. Note, however, that across discontinuities two different elements of fluid may have undergone different dissipative processes. Consequently, the adiabatic law may be different for the two particles.

In order to introduce the subject of shock waves in a manner most appropriate to the present discussion, it will be convenient to first discuss waves of small amplitude.

For reference, the continuity and momentum equations for one-dimensional flow are repeated:

$$\frac{\partial}{\partial x}(\rho u)+\frac{\partial\rho}{\partial t}=0 \tag{4-9}$$

and

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}=-\frac{1}{\rho}\frac{\partial P}{\partial X} \tag{4-10}$$

Assume that there exists an everywhere uniform and stationary fluid of (initial) density ρ_o. It is now desired to determine how the fluid reacts when a small pressure disturbance is created. This is the usual acoustic problem. It is instructive to see what assumptions must be made to arrive at the concept of a sound wave.

If the indicated differentiation is carried out in Eq. 4–9, the result is

$$\frac{\partial}{\partial x}(\rho u)=\frac{\partial\rho}{\partial x}u+\rho\frac{\partial u}{\partial x}.$$

If it is assumed that u, the particle velocity, is small, and that the density change at a point is small as a result of a small pressure pulse, the term $\frac{\partial\rho}{\partial x}u$ represents a quantity of second-order compared with $\rho\frac{\partial u}{\partial x}$. Accordingly, it may be neglected. Further, since P is presumed to be a function of ρ only,

$$\frac{\partial P}{\partial t}=\left(\frac{dP}{d\rho}\right)\frac{\partial P}{\partial\rho}.$$

Since $\left(\frac{dP}{d\rho}\right)$, evaluated for an adiabatic change is a slowly varying function of ρ, it will be treated within the framework of the present assumption as a constant, and be denoted by C_o^2. In the momentum equation, Eq. 4–10, the term $u\,\frac{\partial u}{\partial x}$ is also of second order and will be

neglected. Using these assumptions in Eqs. 4–9 and 4–10 leads to

$$\rho\frac{\partial u}{\partial x}+\frac{1}{C_o^2}\frac{\partial P}{\partial t}=0 \qquad (4\text{–}15)$$

and

$$\frac{1}{\rho}\frac{\partial P}{\partial x}+\frac{\partial u}{\partial t}=0. \qquad (4\text{–}16)$$

As a further assumption, consistent with those already made, $\rho\frac{\partial u}{\partial x}$ for example, may be written $(\rho_0+\Delta\rho)\frac{\partial u}{\partial x}$, and the term $\Delta\rho\frac{\partial u}{\partial x}$ is a second order quantity. Neglecting this term results in the pair of linear, partial, differential equations with constant coefficients,

$$\rho_o\frac{\partial u}{\partial x}+\frac{1}{C_o^2}\frac{\partial P}{\partial t}=o \qquad (4\text{–}17)$$

and

$$\frac{1}{\rho_o}\frac{\partial P}{\partial x}+\frac{\partial u}{\partial t}=o \qquad (4\text{–}18)$$

which may be combined into a single equation. Differentiating the first with respect to t, and the second with respect to x, and making use of the fact that

$$\frac{\partial}{\partial t}\left(\frac{\partial u}{\partial x}\right)=\frac{\partial}{\partial x}\left(\frac{\partial u}{\partial t}\right)$$

for continuous functions and derivatives, we combine the pair of equations to give the acoustic wave equation

$$\frac{\partial^2 P}{\partial x^2}=\frac{1}{C_o^2}\frac{\partial^2 P}{\partial t^2} \qquad (4\text{–}19)$$

A solution of this equation requires the substitution of some function that will reduce both sides to an identity. As may be seen by direct substitution, such a function is

$$P=f\ (t-x/C_o) \qquad (4\text{–}20)$$

where the argument of the function is the quantity $t-x/C_o$, and f is an arbitrary function. The exact form of f will depend on the boundary conditions; however, without considering that aspect considerable information can be obtained. In words, Eq. 4–20 states that the pressure in the fluid at any point x, and at any time t, is a function of the specific combination of x and t, given by $(t-x/C_o)$, regardless of the functional form of f. To see the meaning of this, let

$$t-x/C_o=w.$$

Then

$$P=f(w)$$

and for all values of x and t which make w a constant, the pressure P is also a constant and equal to the same value, because a function of a constant is a constant. Let w be given a set of constant values, such as w_0, w_1, w_2, etc.; then,

$$x=C_o t+C_o w_i \qquad (4\text{–}21)$$

where w_i is one of the values of the series w_0, w_1, etc. If x is plotted against t for different values of w, the result is a set of straight lines, all having the same slope, as shown in Fig. 4–7.

Also note that because of $P=f\ (w_i)$, each line is also a line of constant pressure. The form of Eq. 4–21 shows that C_o is a speed factor, because (speed) × (time) gives distance. Consider then, the point a on line w_4. Let the pressure on this line (everywhere on the line) have the value P_4. This occurs at $x=x_a$, at time $t=t_a$, as shown. As other points are considered in the (x, t) flow field, it is seen that at point b, where $x=x_b$, and $t=t_b$, the pressure is still P_4. That is, the same pressure has been trans-

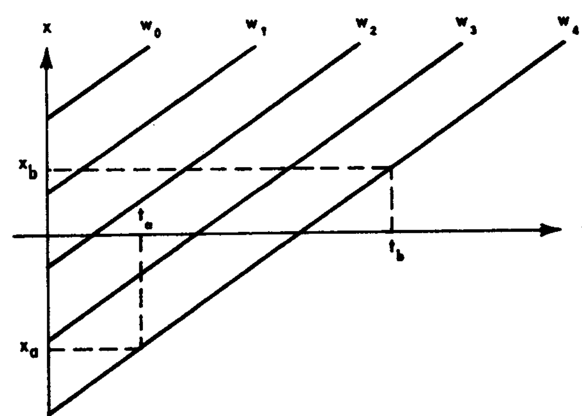


Figure 4–7. Plot of x Against t for Different Values of w

mitted from point a to point b. Since the speed of transmission is

$$\frac{x_b - x_a}{t_b - t_a}$$

using Eq. 4–21, the

$$\text{speed of transmission} = \frac{C_o(t_b - t_a)}{(t_b - t_a)} = C_o$$

showing that C_o is the speed of transmission of the pressure pulse. Since the lines given by $x = C_o t + C_o w_1$ are straight lines, it can be seen that C_o, called the speed of sound, is the same everywhere in the flow field. It is also seen that by holding x constant and varying the time, the pressure at a point changes with time. The pressure pulse may then be envisioned as being transmitted as shown in Fig. 4–8, where the pulse is moving to the right with the speed C_o. That is, energy is exchanged between particles to transmit the pressure; however, the movement of each particle need only be small. This is well illustrated by the familiar example of an ever-widening disturbance created on the surface of a still pool of water.

To examine the motion of each particle, consider Eq. 4–18. Then, with $P = f(t - x/C_o)$,

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho_o}\frac{\partial P}{\partial x} = -\frac{1}{\rho_o} f'\left(t - x/C_o\right)\left(\frac{-1}{C_o}\right) \tag{4–22}$$

where $f'(t - x/C_o)$ is the derivative of f with regard to its argument $(t - x/C_o)$. In order to determine the variation in u at a point, we integrate this equation with respect to t, holding x fixed. This gives

$$u = \frac{1}{\rho_o C_o} f\left(t - x/C_o\right)\Big|_{P=P_o}^{P=P} \tag{4–23}$$

or

$$u = \frac{1}{\rho_o C_o}\left[P - P_o\right] \tag{4–24}$$

where the initial values of u and P are taken as zero and P_o, respectively.

To effect the integration of Eq. 4–22 with respect to time, as above, write

$$t - x/C_o = z$$

then

$$\frac{\partial u}{\partial t} = \frac{1}{\rho_o C_o} f'(z)$$

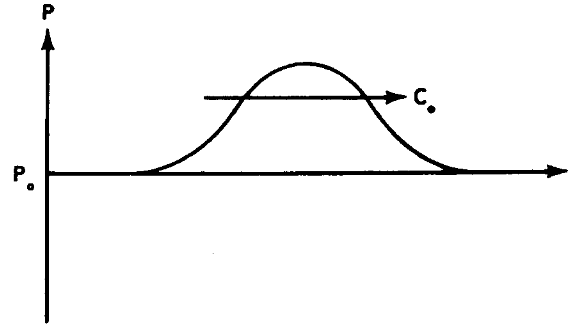


Figure 4–8. Transmission of Pressure Pulse in Point-Time Field

and

$$f'(z) = \frac{\partial f}{\partial t}\frac{\partial t}{\partial z} = \frac{\partial f}{dt}$$

since $\partial t/\partial z = 1$, and the result follows.

From Eq. 4–24 it is seen that u is small, compared with the speed of transmission, for small variations in P_o. To examine some numerical values recall that the sound speed C_o, is given by

$$C_o = \sqrt{\frac{dP}{d\rho}}.$$

Using the adiabatic equations of state for air and water gives $C_o = 1{,}100$ ft/sec. for air and $C_o = 5{,}000$ ft/sec. for water, at near standard conditions. Since the densities of the two media are so different, Eq. 4–24 shows that the particle velocity is much less in water. If $\rho_o = 2.0 \times 10^{-3}$ slugs/cu ft for air, and $\rho_o = 2.0$ slugs/cu ft for water, the same pressure difference of (for example) one hundredth of an atmosphere = 20 lb/sq ft, produces particle velocities, induced by the passage of the pressure wave, equal to,

$$u_{water} = 2 \times 10^{-3} \text{ ft/sec.}$$

$$u_{air} = 10 \text{ ft/sec.}$$

4–2.3.4. Basic Spherical Wave Equations

Up to this point, the discussion has dealt with one-dimensional flow along a specified axis. Therefore, the waves produced have been plane waves, and the equations presented apply only to that case. [Observe that $P = f(t + x/C_o)$ is also a solution to the previous equation. This corresponds, physically, to a wave traveling in

the reverse direction.] Of even greater interest is the case of spherical waves. Fortunately, if it is assumed that the spherical waves are symmetrical and depend only on radius and time, the equations still depend on only one space variable. Let this variable be r, and by reasoning similar to that already employed, a set of equations may be derived that express the continuity and momentum relations. If these equations are linearized in the same way as the plane wave case, the following are obtained:

$$\frac{\partial u}{\partial t}=-\frac{1}{\rho_o}\frac{\partial P}{\partial r} \tag{4–25}$$

and

$$\frac{1}{C_o^2}\frac{\partial P}{\partial t}=-\rho_o\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\frac{\partial u}{\partial r}) \tag{4–26}$$

which, when combined, give,

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial P}{\partial r}\right)=\frac{1}{c_o^2}\frac{\partial^2 P}{\partial t^2} \tag{4–27}$$

where u now means the radial speed, $u=\frac{\partial r}{\partial t}$, for a given particle. It may be verified by differentiation that a solution of Eq. 4–27 is

$$P=\frac{1}{r}f\,(t-r/C_o). \tag{4–28}$$

Using exactly the same argument as before, it is seen that C_o is the speed of the spherical wave, but that now the amplitude decreases with radius because of the factor $(1/r)$. This is obviously caused, physically, by the greater area over which the advancing disturbance is spread. Integrating Eq. 4–25 with regard to t, and using the functional expression just found for P gives

$$u=\frac{P-P_o}{\rho_o C_o}+\frac{1}{\rho_o r}\int_0^t[P(r,t')-P_o]dt'$$

where t' is a variable of integration. Although integration cannot be performed explicitly, as in the plane case, it is seen that the velocity in the fluid u, at position r, is not only a function of the pressure difference at that time, but also a function of all previous pressures that reached the point prior to time$=t$. This is shown by the presence of the integral. That is, the velocity u, called the after flow, will exist even after the local pressure difference has fallen to zero. Further, u will equal zero only when P falls below P_o. This illustrates one significant effect of a spherical source. It also serves to show why the blast problem leads to mathematical difficulties, for a complete evaluation of pressures and flow at points behind (after the wave has passed) the wave front is clearly only possible by considering the properties of the source which generate the wave. Further, any source will be affected by the fluid surrounding it, and it is seen that a coupling exists between the cause and effect. In the blast computations to be considered later, this coupling will be seen to complicate, and determine, the boundary conditions.

In the blast problem, only weak sources produce acoustic waves. In the cases of interest, and in relation to an explosion, the pressure differences created by the passage of a wave front are too great to consider the linearized equations just discussed. In fact, the nonlinear character of the flow field, together with considerations of viscosity and heat transfer, lead to the formation of shock waves. To see, from a physical viewpoint, how this happens, consider the following argument.

In the linearized treatment, the sound speed $C(x,t)$ was replaced by a constant value, C_o, evaluated at the equilibrium state. In other words, the transmission speed was assumed to be independent of the pressure and the state of motion of the fluid. These assumptions lead to the conclusion that the $C=C_o$ was a constant in a fixed coordinate system. On the other hand, if C is permitted to vary and is measured with respect to a set of coordinates moving with the fluid at the point in question, matters become more complex. Since $P=P\ (\rho)$ is an adiabatic relationship, P is expected to increase at an increasing rate with ρ. That is, $\frac{dP}{d\rho}$ is positive and increases with increasing compression. Accordingly, the sound speed increases

with increasing compression. The great significance of this effect is shown in the following discussion, based on Ref. 4.

Consider subsequent spatial positions of the same wave, as shown in Fig. 4–9. Compression traveling to the right, as in position (1), will have the speed C_a, relative to the fluid, at point a. The absolute speed of compression at point a is, therefore, u_a+C_a, where u_a is the particle speed. Point b represents the pressure wave with speed of transmission u_b+C_b. Since point b is a point of higher compression than point a, u_b and C_b are both higher than at point a. Hence, as measured in absolute coordinates, the pressure pulse is being transmitted faster than at point a. Correspondingly, the sequence of events is shown in (2) and (3), where the crest of the wave has overtaken the valley. Here there is an exceedingly sharp wave front, across which quantities vary in an almost discontinuous fashion. The steepness of this wave front generates large gradients, from which it could be expected that heat conduction and viscosity would enter the picture. Because it is known that they do, to a significant extent, the elementary analysis just considered is not satisfactory for a complete evaluation of shock waves. However, it does point out the significant fact that strong compression waves lead to shock waves. Conversely, the argument also shows that rarefaction waves cannot produce shock waves. This aspect of the discussion is concluded by the observation that spherical waves, even though strongly initiated, will eventually approach sound waves because the energy density from a finite source is spread out over an ever expanding sphere.

4–2.3.5. *Various Approaches to the Blast Problem for Free Air Bursts*

a. General

The discussion of physical aspects in the preceding paragraph and the nonlinear character of the basic equations indicate that shock waves will develop. Further, it is clear that after the shock front has started to develop, the heat conduction effect and viscosity must become important because of the high gradients existing in pressure, temperature, etc., at the wave front. It would seem that an obvious solution would be to include the viscosity and conduction effects in the basic equations from the beginning, and to then solve the resulting partial differential equations. The resulting solutions would automatically account for the shock fronts and all aspects of the flow. Unfortunately, such an approach is far beyond the present applications of nonlinear differential equations. Even from a purely numerical viewpoint, the highest speed computers would be useless in a problem of this generality. Of necessity, then, approximations are made in obtaining solutions to the blast problem. Since the various methods are approximations, they are not unique, and differences in principal as well as in computational techniques would be expected.

It has already been indicated that none of the authoritative works in the field has attempted to solve the complete problem. Instead, the shock waves are treated as mathematical discontinuities, which serve as free boundaries between regions of assumed adiabatic flow fields. The term free boundary means that these discontinuities are not known

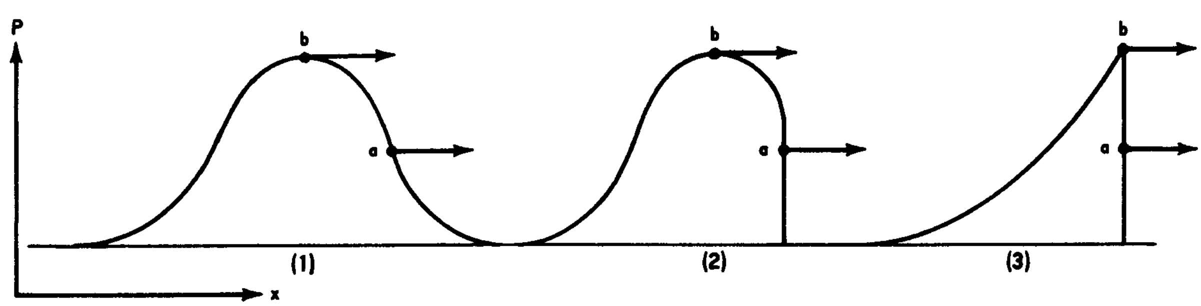


Figure 4–9. Compression Speed vs Transmission Speed

in advance, but must be determined as the solution proceeds. Indeed, this one fact accounts for some of the major difficulties encountered in problems of this type, both from a computational and theoretical viewpoint.

It should be pointed out here that von Neumann's scheme of fictitious viscosity is a departure from all former techniques. While this technique does not treat shocks as a mathematical discontinuity, neither does it attempt to solve the governing differential equations in all their generality. This fictitious viscosity method will be discussed in following subparagraphs. Since shock waves, treated as mathematical discontinuities, play such an important role in blast calculations, it is worthwhile to describe the conditions under which they exist. The physical basis for their formation has already been discussed. The analytical conditions existing at a shock front will now be examined. In order to discuss shock waves from an analytical viewpoint, it is necessary to develop the Rankine-Hugoniot equations. These are treated in many places (Ref. 3, for example) and will be repeated here only to the extent necessary to observe the physical implications behind them.

Consider, for illustration of the analytical conditions existing at a shock front, the case of a plane wave advancing into a region at rest. The side of the discontinuity facing the undisturbed flow is called the front of the shock wave. As this front passes, the particles of fluid have their properties changed. Hence, viewed from an absolute coordinate system, a condition of nonsteady flow exists. If it is assumed that the front advances at a uniform speed, U, with respect to fixed axes, then an observer traveling with the front would observe a condition of steady state. Let the subscript "o" refer to properties of the fluid in the undisturbed state, and let properties without a subscript refer to the condition after passage of the front. In Fig. 4–10, u represents the particle speed with respect to fixed coordinates, P the pressure, and ρ the density. E is the internal energy per unit mass. The shock front is shown moving to the right into the undisturbed fluid, at speed U with respect to fixed coordinates.

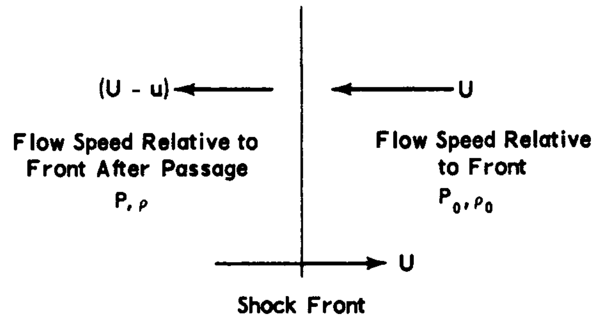


Figure 4–10. Movement of Shock Front in Undisturbed Fluid

The conservation of mass is expressed by the fact that the mass entering the front must leave the front. Therefore, for a unit area,

$$\rho\ (U-u) = \rho_o\, U. \qquad (4\text{–}29)$$

Newton's law may be expressed in the form: change of momentum equals impulse. In time dt, the mass crossing the boundary is

$$\rho\ (U-u)\ dt$$

and the momentum carried into the disturbed region in time dt is the product of the mass transported and the absolute speed of transport (because Newton's law is true with respect to absolute coordinates). The momentum transported out is, therefore,

$$\rho\ (U-u)\, u dt$$

and in a similar manner, the momentum transported into the boundary is

$$\rho_o\, U(o)\, dt = 0$$

because the absolute speed before the shock is zero. The impulse in time dt is

$$[P-P_o]dt$$

and equating the two expressions gives

$$\rho\ (U-u)\ u = P - P_o$$

but from the continuity equation, Eq. 4–29, this may be written

$$\rho_o\, Uu = P - P_o. \qquad (4\text{–}30)$$

To establish the energy equation, we require that the work done on an element as it passes through the boundary is equal to the total change in energy. The work, in time dt, is

$$Pudt$$

noting that the work of P_o is zero. The total change in energy in time dt is

$$\rho_o\, Udt[(E-E_o) + \tfrac{1}{2}u^2].$$

Equating the two expressions gives

$$Pu = \rho_o U(E - E_o) + \frac{1}{2}u^2$$

which, by elimination of u and U by use of Eqs. 4–29 and 4–30, may be written

$$E - E_o = \frac{1}{2}\left(P - P_o\right)\left(\frac{1}{\rho_o} - \frac{1}{\rho}\right). \qquad (4\text{–}31)$$

Eqs. 4–29, 4–30, and 4–31 show that a solution exists in the flow field for which the variables are not zero. That is, the basic laws of physics show that a discontinuous flow is possible. It is these equations that are needed as boundary conditions to relate the flow on one side of a discontinuity to the flow on the other, when solving the differential equations of fluid motion. Solving the first two explicitly for u and U gives,

$$U = \left[\left(\frac{\rho}{\rho_o}\right)\frac{P - P_o}{\rho - \rho_o}\right]^{1/2}$$

and

$$u = \frac{\rho - \rho_o}{\rho} U.$$

Thus, the shock and particle speeds may be determined in terms of the stated variables. This is what was meant by the term free boundaries. The speed, and hence position, of the boundaries are determined only after the flow variables are determined in the solution of the differential equations. Such solutions frequently require trial-and-error techniques which are, at best, very time consuming.

If it is assumed that adiabatic (but different adiabatic) conditions exist on either side of the shock wave, the energy terms may be expressed as

$$E = \frac{1}{\gamma - 1}\,\frac{P}{\rho}$$

and

$$E_o = \frac{1}{\gamma - 1}\,\frac{P_o}{\rho_o}$$

where γ is the ratio of specific heats. With these two relations and the Rankine-Hugoniot equations (Eqs. 4–29, 4–30, and 4–31), many useful relations may be developed. This is shown, for example, in Ref. 5. Some explicit expressions, taken from Ref. 6, are

$$\frac{\rho}{\rho_o} = \frac{1 + 6y}{6 + y} \qquad (4\text{–}32)$$

$$\frac{U^2}{a_o^2} = \frac{1 + 6y}{7} \qquad (4\text{–}33)$$

$$\frac{u}{U} = \frac{5(y - 1)}{1 + 6y} \qquad (4\text{–}34)$$

$$\frac{c^2}{a_o^2} = y\,\frac{6 + y}{1 + 6y} \qquad (4\text{–}35)$$

where the equations give, respectively: the density ratio across the shock (4–32); the Mach number of the advancing front, referred to the speed of sound in the undisturbed fluid (4–33); the ratio of the particle velocity to the shock speed (4–34), and the ratio of the speed of sound behind the shock front to the speed of sound in the undisturbed fluid (4–35). In these equations, the terms not previously defined are:

a_o = speed of sound in the undisturbed flow. Under the present adiabatic assumptions, a_o may be expressed as

$$a_o = \left(\frac{\gamma P_o}{\rho_o}\right)^{1/2}.$$

c = speed of sound behind the shock front.

$$c = \left(\frac{\gamma P}{\rho}\right)^{1/2}.$$

y = ratio of the pressure after the shock to the pressure ahead of the shock, $y = P/P_o$.

γ = ratio of specific heats, taken equal to 7/5 for these expressions. It is a well-known fact that $\gamma = 7/5 = 1.4$ is an adequate representation for air, provided the temperatures are not too high.

It is observed that these important flow parameters have all been expressed in terms of the pressure ratio across the shock wave.

Returning now to a discussion of possible types of solutions for the blast problem, we shall consider first the point source, strong blast solution of von Neumann, as discussed in Ref. 7.

b. J. von Neumann's Solution of the Point Source, Strong Blast Case

Some of the fundamental work performed on blast waves during World War II is represented by Ref. 7, which is readily accessible. The first topic of the report is the case under con-

sideration, introduced most effectively by quoting, in part, von Neumann's own words.

"The conventional picture of a blast wave is this: In a homogeneous atmosphere a certain sphere around the origin is suddenly replaced by homogeneous gas of much higher pressure. The high pressure area will immediately begin to expand against the surrounding low pressure atmosphere and send a pressure wave into it. As the high pressure area expands, its density decreases and with it the pressure; hence the effects it causes in the surrounding atmosphere weaken. As the pressure wave expands spherically through the atmosphere it is diluted over spherical shells of ever-increasing radii, and hence its intensity (the density of energy, and with it the over-pressure) decreases continuously also. This pressure wave is known (both theoretically and experimentally) to consist at all times of a discontinuous shock wave at the front, and to weaken gradually as one goes backward from that front.

"This description of the blast wave caused by an explosion is somewhat schematic, since the high pressure area caused by an explosion is not produced instantaneously, nor is its interior homogeneous, nor is it in general exactly spherical. Nevertheless, it seems to represent a reasonable approximation of reality.

"Mathematically, however, this approximate description offers very great difficulties. To determine the details of the history of the blast; that is, of its decay, the following things must be computed: (1) the trajectory of the shock wave; that is, of the front of the blast wave; and (2) the continuous flow of air behind the shock (ahead of the shock the air is unperturbed and at rest). This requires the solution of a partial differential equation bounded by the unknown trajectory (1). Along this trajectory the theory of shocks imposes more boundary conditions than are appropriate for a differential equation of the type (2), and this overdetermination produces a linkage between (1) and (2) which should permit one to determine the trajectory of (1) and to solve (2). To this extent the problem is a so-called "free boundary" partial differential equation problem. However, the situation is further complicated by the fact that at each point (2) the local entropy is determined by the entropy change the corresponding gas underwent when it crossed the shock (1); that is, by the shock strength at a certain point of (1). The latter depends on the shape of the trajectory (1), and the entropy in question influences the coefficients of the differential equation (2). Hence the differential equation (2) itself depends on the shape of the unknown trajectory (1). This dependence cannot be neglected as long as the entropy change caused by the shock is important; that is, as long as the shock is strong (in air a shock can be considered "strong" if the shock pressure exceeds 3 atm). Mathematically such problems are altogether inaccessible to our present analytical techniques. For this reason the general problem of the decay of blast has been treated only by approximate analytical methods, or numerically, or by combinations of these.

"For very violent explosions a further simplification suggests itself, which changes the mathematical situation very radically. For such an explosion it may be justified to treat the original, central, high pressure area as a point. Clearly, the blast coming from a point, or rather from a negligible volume, can have appreciable effects in the outside atmosphere only if the original pressure is very high. One will expect that, as the original high pressure sphere shrinks to a point, the original pressure will have to rise to infinity. It is easy to see, indeed, how these two are connected. One will want the energy of the original high pressure area to have a fixed value E_o, and as the original volume containing E_o shrinks to zero, the pressure in it will have to rise to infinity. It is clear that of all known phenomena nuclear explosions come nearest to realizing these conditions."

The investigation presented in Ref. 7 concerning the decay of a blast wave due to a point explosion of energy E_o was largely taken from the following sources: G. I. Taylor, Proc. Royal Soc., British Report RC–210, June 27, 1941; and John von Neumann, NDRC, Div. B, Report AM–9, June 30, 1941. Important simplifications (in particular, the use of the variable of Eq. 2.44) are due to G. Y. Kynch, British Report BM–82, MS–69, Sept. 18, 1943. The results

were generalized by J. H. van Vleck, NDRC, Div. B, Report AM-11, Sept. 15, 1942. Compare also the later work of G. I. Taylor, Proc. Royal Soc. (London), *A201*, 159 (1950).

One of the most significant aspects of the solution given by von Neumann is the use of dimensional similarity to reduce the complexity of the problem. Since he deals with a point source and considers very high pressures, the initial air pressure before burst, P_o is neglected. These assumptions permit a grouping of variables which leads to a set of ordinary, rather than partial equations. The report concludes with a set of formulae which may be used to compute the shock and flow parameters.

c. H. Bethe's Solution for Small $(\gamma-1)$

A method discussed by H. Bethe, in Ref. 7, is more general than von Neumann's solution. It is based on the fact that the term $(\gamma-1)$ may be considered small in many applications. Here, again, the best description of the method is afforded by the author's introductory remarks:

"The solution given in von Neumann Point Source Case is only valid for an exact point source explosion, for constant γ, for constant undisturbed density of the medium, and for very high shock pressures. It is very desirable to find a method which permits the treatment of somewhat more general shock wave problems and thereby comes closer to describing a real shock wave. The clue to such a method is found in the very peculiar nature of the point source solution of Taylor and von Neumann. It is characteristic for that solution that the density is extremely low in the inner regions and is high only in the immediate neighborhood of the shock front. Similarly, the pressure is almost exactly constant inside a radius of about 0.8 of the radius of the shock wave.

"It is particularly the first of these facts that is relevant for constructing a more general method. The physical situation is that the material behind the shock moves outward with a high velocity. Therefore, the material streams away from the center of the shock wave and creates a high vacuum near the center. The absence of any appreciable amount of material, together with the moderate size of the accelerations, immediately leads to the conclusion that the pressure must be very nearly constant in the region of low density. It is interesting to note that the pressure in that region is by no means zero, but is almost one-half of the pressure at the shock front.

"The concentration of material near the shock front and the corresponding evacuation of the region near the center is most pronounced for values of the specific heat ratio γ close to 1. It is well-known that the density at the shock increases by a factor

$$\frac{\rho_s}{\rho_o}=\frac{\gamma+1}{\gamma-1} \tag{4-36}$$

This becomes infinite as γ approaches unity. Therefore, for γ near 1 the assumption that all material is concentrated near the shock front becomes more and more valid. The density near the center can be shown to behave as $(\gamma-1)/r^3$, where r is the radius.

"The idea of the method proposed here is to make repeated use of the fact that the material is concentrated near the shock front. As a consequence of this fact, the velocity of nearly all the material will be the same as the velocity of the material directly behind the front. Moreover, if γ is near 1, the material velocity behind the front is very nearly equal to the shock velocity itself; the two quantities differ only by a factor $2/(\gamma+1)$. The acceleration of almost all the material is then equal to the acceleration of the shock wave; knowing the acceleration one can calculate the pressure distribution in terms of the material coordinate; i.e., the amount of air inside a given radius. The calculation again is facilitated by the fact that nearly all the material is at the shock front and therefore has the same position in space (Eulerian coordinate).

"The procedure followed is then simply this: we start from the assumption that all material is concentrated at the shock front. We obtain the pressure distribution. From the relation between pressure and density along an adiabatic, we can obtain the density of each material element if we know its pressure at the present time as well as when it was first hit by the shock. By integration of the density we can then find a more accurate value for the

position of each mass element. This process could be repeated if required; it would then lead to a power series in powers of $\gamma - 1$.

"The method leads directly to a relation between the shock acceleration, the shock pressure, and the internal pressure near the center of the shock wave. In order to obtain a differential equation for the position of the shock as a function of time, we have to use two additional facts. One is the Hugoniot relation between shock pressure and shock velocity. The other is energy conservation in some form. In some applications such as that to the point source solution itself, we may use the conservation of the total energy which requires that the shock pressure decrease inversely as the cube of the shock radius (similarity law). On the other hand, if there is a central isothermal sphere no similarity law holds, but we may consider the adiabatic expansion of the isothermal sphere and thus determine the decrease of the central pressure as a function of the radius of the isothermal sphere. If we wish to apply the method to the case of variable γ without isothermal sphere, we may again use the conservation of total energy, but in this case the pressure will not be simply proportional to $1/Y^3$, where Y is the shock radius.

"As has already been indicated, the applications of the method are very numerous. The case of not very high shock pressures can also be included; in this case the density behind the shock wave does not have the limiting value of Eq. 4–36 but depends itself on the shock pressure. This does not prevent the application of our method as long as the density increase at the shock is still very large so that most of the material is still near the shock front.

"The only limitations of the method are its moderate accuracy and the possible complications of the numerical work. The accuracy seems satisfactory up to γ about 1.4. For the point source, a direct comparison with the exact solution is possible."

The most significant aspect of H. Bethe's solution is the fact that, although desired for conditions near $\gamma = 1$, it holds reasonably well for the case of $\gamma = 1.4$, the standard air value. The author shows that it agrees with von Neumann, if in von Neumann's solution γ is allowed to approach 1.

d. H. Bethe's, K. Fuchs' Solution for Small Blast Pressure

Ref. 7 is also the source of this theory. The purpose of the analysis was to provide an asymptotic solution that reduces to ordinary acoustic theory in the limit, as the radius of the blast sphere becomes large. Another reason given for the technique is that it may be used to indicate a suitable stopping point in a purely numerical computation. This point is reached when solution by machine has progressed sufficiently to make numerical techniques wasteful of machine time; because from this point, asymptotic, appropriate formulas are adequate. For further information, Ref. 7 should be consulted.

e. The Method of Kirkwood and Brinkley

Developed by the authors during World War II, this method differs in principle from those mentioned above, because the authors are specifically interested in the blast from high explosives rather than nuclear explosions. It is applicable to either air or water. The method is summarized in Ref. 5, and the original paper is listed herein as Ref. 8. The report is one in a long series on the same general subject by the same authors. Refs. 5 and 8 each give additional references.

The Kirkwood-Brinkley theory has become somewhat of a standard for high explosive work, and although experimental discrepancies have been reported, it still remains one of the best available means of approximating the physical occurrence of blast.

The theory is based upon nonviscous theory outside shock fronts, and uses the equations of motion and the equation of continuity in spherical coordinates. When these two equations are evaluated at the shock front, they represent two relations for the unknown radial velocity u and pressure P, and their derivatives. The Rankine-Hugoniot equation provides one more relationship, making three equations available. (It should be observed that the other Rankine-Hugoniot equations do not supply the needed information, for they introduce additional state variables.)

In developing the equations, the initial and boundary conditions are chosen to correspond to adiabatic explosion at constant volume. While these do not coincide exactly with real explosives, the inaccuracies introduced decrease with blast radius.

The fourth required relationship between the derivatives is achieved approximately by requiring that certain similarity conditions be satisfied. The authors point out in their basic report, Ref. 8, that it is futile to seek a fourth relation between the partial derivatives that does not involve a solution of the basic equations. They go on to show, however, that an approximate relationship can be achieved on physical grounds. The exact form of the relationship is discussed in detail in Ref. 8; physically, it amounts to choosing a functional form for the shape of the shock wave decay, and then determining unknown constants so that the basic equations are satisfied as nearly as possible. As the authors point out, such a procedure is similar to the Rayleigh method, in which an assumed solution is chosen, subject to the determination of constants.

The report concludes with a discussion of specific procedures for computing shock wave parameters. It should also be remarked that this theory is particularly suitable for extending measured data out to greater blast radii. This use, in fact, has become one of the major applications of the theory.

f. The Fictitious Viscosity Method of J. von Neumann and R. Richtmyer

In Ref. 9 von Neumann and Richtmyer introduce a significantly new concept for the calculation of flow fields bounded by, and containing, shock waves. A direct quotation from the introduction of this basic paper is appropriate.

"In the investigation of phenomena arising in the flow of a compressible fluid, it is frequently desirable to solve the equations of fluid motion by stepwise numerical procedures, but the work is usually severely complicated by the presence of shocks. (10) The shocks manifest themselves mathematically as surfaces on which density, fluid velocity, temperature, entropy and the like have discontinuities; and clearly the partial differential equations governing the motion require boundary conditions connecting the values of these quantities on the two sides of each such surface. The necessary boundary conditions are, of course, supplied by the Rankine-Hugoniot equations, but their application is complicated because the shock surfaces are in motion relative to the network of points in space-time used for the numerical work, and the differential equations and boundary conditions are nonlinear. Furthermore, the motion of the surfaces is not known in advance but is governed by the differential equations and boundary conditions themselves. In consequence, the treatment of shocks requires lengthy computations (usually by trial and error) at each step, in time, of the calculation.

"We describe here a method for automatic treatment of shocks which avoids the necessity for application of any such boundary conditions. The approximations in it can be rendered as accurate as one wishes, by suitable choice of interval sizes and other parameters occurring in the method. It treats all shocks, correctly and automatically, whenever and wherever they may arise.

"The method utilizes the well-known effect on shocks of dissipative mechanisms, such as viscosity and heat conduction. (Lord Rayleigh (11) and G. I. Taylor (12) showed, on the basis of general thermodynamical considerations, that dissipation is necessarily present in shock waves. Later, R. Becker (13) gave a detailed discussion of the effects of heat conduction and viscosity. Recently, L. H. Thomas (14) has investigated these effects further in terms of the kinetic theory of gases.) When viscosity is taken into account, for example, the shocks are seen to be smeared out, so that the mathematical surfaces of discontinuity are replaced by thin layers in which pressure, density, temperature, etc., vary rapidly but continuously. Our idea is to introduce (artificial) dissipative terms into the equations so as to give the shocks a thickness comparable to (but preferably somewhat larger than) the spacing of the points of the network. Then the differential equations (more accurately, the

Next Page

corresponding difference equations) may be used for the entire calculation, just as though there were no shocks at all. In the numerical results obtained, the shocks are immediately evident as near-discontinuities that move through the fluid with very nearly the correct speed and across which pressure, temperature, etc., have very nearly the correct jumps."

It should be noted that as useful as this concept is, it depends explicitly upon the numerical integration of the differential equations. The ability to carry out the numerical solutions has resulted from the great improvements in computers since World War II. Present day machines are not only much faster, but are more reliable.

It should be noted, too, that the present method is much more general than the other methods. Where the older methods assume the outward progress of the shock wave, they neglect the possibility (in most cases) of the formation of other, following shocks. In the present method, these additional shocks are automatically accounted for.

g. H. Brode's Application of the Fictitious Viscosity Method

H. Brode (Ref. 15) uses the fictitious viscosity method of Ref. 9 to carry through very complete solutions for the point source method. The author points out that solutions of the blast wave problem are available for point source-strong wave, and point source-weak wave. These are discussed in Ref. 7.

It will be recalled that mathematical difficulties lead to the need for simplifications in the early work. In particular, the shock problem of free boundaries presented an extremely difficult computational problem. With the disclosure of Ref. 9, complete new areas were opened for study and analysis. A detailed treatment of the point source case is given in Ref. 15. The paper outlines the approach and discusses the numerical integration scheme used. A very significant aspect of the paper is the presentation of a rather large number of numerical results. The presentation is given primarily in terms of nondimensional quantities from which detail calculations may be made. Following are some of the results presented in the report, either in the form of curves, explicit equations, or both.

1. Particle velocity at the shock front vs radius parameter.
2. Overpressure at the shock front vs radius parameter.
3. Dynamic pressure at the shock front vs radius parameter.
4. Pressure within the flow field as a function of time and distance, in terms of a time parameter and a radius parameter.
5. Particle velocity as a function of position and time.
6. Density as a function of position and time.
7. Positive and negative phase duration. That is, the times during which the overpressure is positive or negative.
8. Positive impulse.
9. Negative impulse.

In these presentations, nondimensional units for time and distance are normally used, so that the curves may be used for many cases of interest.

From both a theoretical and practical computational viewpoint, this paper is highly recommended as a working tool for blast computations. The paper concludes by examining the case of a finite-size source, and remarks on the basic differences in the mathematical models represented by the point and finite-size sources.

h. H. Brode's Application of the Fictitious Viscosity Method to a Finite-Size Charge of High Explosive

H. Brode's work on solutions of the point source method (Ref. 15) were extended to include the case of a finite-size sphere of high explosive as the initiating energy source (Ref. 16). The hydrodynamic equations were solved numerically, using the artificial viscosity concept. Results are presented graphically in most cases. The author also points out the significant fact that scaling laws are less appropriate in a blast computation based on a finite-size high explosive charge. This is true because the boundary conditions depend on the mass of the HE, and the effects, it has been found, extend out to low pressure levels. The

GLOSSARY
of Terminal Ballistics Terms (U)

A

air burst. Any burst in the air, but usually having reference to the bursting of a projectile or bomb above the ground with resulting spray of fragments.

aircraft. **1.** In a broad sense, any machine or craft designed to go through the air (including, in some instances, outer space), given lift by its own buoyancy (as with airships), or by dynamic reaction of air particles over and about its surfaces, or by reaction to a jet stream or other fluid jet. **2.** *Restrictive*—A powered, fixed-wing airplane.

airframe. The structural components of an airplane or missile, including the frame work and skin of such parts as the fuselage, empennage, wings, landing gear (minus tires), and engine mounts.

airspeed. The velocity at which an aircraft is traveling through the atmosphere (air). It is entirely independent of any distance covered on the surface of the earth.

aluminized explosive. An explosive to which aluminum has been added. The aluminum, in flaked or powdered form, is incorporated into the explosive to increase the blast effect. Examples of aluminized explosives include ammonal, HBX's, and tritonal.

ambient. Surrounding, encompassing, as in ambient air, ambient temperature.

ammunition. **1.** A generic term which includes all manner of missiles to be thrown against an enemy, such as bullets, projectiles, rockets, grenades, torpedoes, bombs, and guided missiles, along with their necessary propellants, primers, fuzes, detonators and charges of conventional explosive, nuclear explosive, chemical or other materials. **2.** In the broadest sense the term is not limited to those materials to be thrown, nor to use against an enemy, but includes, in addition to the items and materials given in sense **1**, all explosives, explosive devices, pyrotechnics and pyrotechnic devices. The purpose is not limited and includes, in addition to direct use against an enemy, such uses as illumination, signaling, saluting, mining, digging, cutting, accelerating, decelerating, separating, catapulting personnel or materiel, operating or stopping mechanisms, demolition, decoying, practice, training, guarding, game hunting, and pure sport. **3.** In the most restricted sense the term includes a complete round and all its components; that is, the material required for firing a weapon such as a pistol, rifle, or cannon, from which a projectile is thrown for inflicting damage upon an enemy. Generally the term is used or taken in its broadest sense (sense **2**) unless a more restricted sense is indicated or is implied by the context.

antiarmor. Of ammunition, bombs, bullets, projectiles, or the like: Designed to defeat armor and other resistant targets.

antimechanized defense. All means used for defense against armored combat vehicles. It may include such means as armored units, antitank weapons and grenades, field artillery, antiaircraft artillery, ditches, traps, mine fields, and any other means available. Also known as antitank defense.

antipersonnel. (apers) Of projectiles, bombs, mines, grenades, or the like: Designed to kill, wound, or obstruct personnel.

antitank. (AT) Used, or designed to be used, against tanks.

antitank weapon. Any weapon designed or suitable for use against tanks or other armored vehicles. Antitank rockets, antitank grenades, and antitank guns are examples of antitank weapons.

applique armor. Material or attachment which can be installed on a tank to give it additional protection against kinetic or nonkinetic energy ammuntion.

area target. A target consisting of an area, such as an entire munitions factory, rather than a single building or similar point target.

armor. **1.** Any physical protective covering, such as metal, used on tanks, airplanes, etc., or on persons, against projectiles or fragments. *See:* **armor, body, fragmentation protective; steel armor plate. 2.** Armored units or forces. 3. In a weapon system, that component that gives protection to the vehicle or the weapon on its way to the target. In sense **1,** conventional steel armor is classified according to its physical and metallurgical structure, as face hardened or homogeneous. It is also classified according to its method of fabrication, as cast or rolled. In sense **3,** the armor may consist of armor (sense **1**) or any other protective device or technique, such as "chaff," diversionary attack, speed, etc.

armor, body, fragmentation protective. Armor especially designed to provide fragmentation protection to vital areas of the body. Usually provided in the form of garments which may contain steel, nylon, or other resistant materials.

armor castings. A type of armor frequently used when complicated shapes are involved. Such castings are made of high alloy steel and are so heat treated as to have the properties of armor plate. May be either the homogeneous or face-hardened type. *See:* **armor.**

armor defeating. A term similar to anti-armor, sometimes applied to any of several types of ammunition, having for its principal purpose the defeat of armor protection of armored vehicles or ships. Types of such ammunition are armor-piercing, HEAT, etc.

armored personnel carrier. An armored vehicle which provides protection from small arms fire and shell fragments; used to transport personnel both on and off the battlefield.

armored vehicle. A wheeled or track-laying vehicle mounting armor plate, used for combat security or cargo. Armored vehicles include tanks, personnel carriers, armored cars, self-propelled artillery and various special purpose vehicles.

armored vehicle damage. *See:* **damage categories.**

armor-piercing. (AP) Of ammunition, bombs, bullets, projectiles, or the like: Designed to penetrate armor and other resistant targets.

armor-piercing, capped. (APC) Of armor-piercing projectiles: Having an armor-piercing cap over the nose. *See:* **cap, armor-piercing.**

armor, spaced. *See:* **spaced armor.**

Army complete penetration. Penetration in which it is possible to see light through the hole made by the projectile, or in which it is possible to see a portion of the projectile in the plate when viewed from the rear.

arrow projectile. *See:* **projectile, arrow.**

aspect angle. The angle formed between the longitudinal axis of a projectile in flight and the axis of a radar beam.

atomic air burst. The explosion of an atomic weapon in the air, at a height greater than the maximum radius of the fireball.

atomic device. Any explosive device that makes use of active nuclear material to cause a chain reaction upon detonation.

atomic surface burst. Atomic missile burst at an elevation such that the fireball touches the ground.

atomic underground burst. The explosion of an atomic weapon with its center beneath the surface of the ground.

atomic underwater burst. The explosion of an atomic weapon with its center beneath the surface of the water.

attitude. The aspect that an aircraft or missile presents at any given moment, as determined by its inclinations about its three axes.

B

ball ammunition. Non-armor-piercing small arms ammunition in which the projectile is solid. It is intended for use against personnel, light material targets, or for training purposes.

ballistic. Pertaining to ballistics (which see) or the motion of missiles.

ballistic coefficient. The numerical measure of the ability of a missile to overcome air resistance. It is dependent upon the mass, the diameter, and the form factor (which see).

ballistic limit. The minimum velocity at which a particular armor-piercing projectile is expected to consistently, completely, penetrate armor plate of given thickness and physical properties, at a specified angle of obliquity. Because of the expense of firing tests and the impossibility of controlling striking velocity precisely, plus the existence of a zone of mixed results in which a projectile may completely penetrate or only partially penetrate under apparently identical conditions, statistical approaches are necessary, based upon limited firings. Certain approaches lead to approximation of the V_{50} Point, that is, the velocity at which complete penetration and incomplete penetration are equally likely to occur. Other methods attempt to approximate the V_0 Point; that is, the maximum velocity at which no complete penetration will occur. Other methods attempt to approximate the V_{100} Point; that is, the minimum velocity at which all projectiles will completely penetrate.

ballistic missile. Specifically, any missile guided especially in the upward part of its trajectory, but becoming a free falling body in the latter stages of its flight through the atmosphere. This missile contains guiding devices, such as preset mechanisms; but it is distinguished from a guided missile in that it becomes a free falling body, subject to ballistic reactions as it descends through the atmosphere. Currently, the term has a strong connotation of a missile designed to travel outside, or in the outer reaches of, the atmosphere, before plunging toward its target.

ballistics. Branch of applied mechanics which deals with the motion and behavior characteristics of missiles; that is, projectiles, bombs, rockets, guided missiles, etc., and of accompanying phenomena. It can be conveniently divided into three branches: interior ballistics, which deals with the motion of the projectile in the bore of the weapon; exterior ballistics, which deals with the motion of the projectile while in flight; and terminal ballistics, which is concerned with the effect and action of the projectile when it impacts or bursts.

bazooka. Popular name applied to the 2.36-inch rocket launcher. The later model 3.50-inch rocket launcher was termed the "super bazooka."

biological warfare. (biowar) 1. Warfare waged by the employment of living organisms, toxic bacteriological products, and chemical plant-growth inhibitors to produce death or casualties in man, animals, or plants. **2.** Defense against such warfare.

black powder. A low explosive consisting of an intimate mixture of potassium or sodium nitrate, charcoal, and sulfur. It is easily ignited and is friction sensitive, but is not of the same sensitivity as primer mixes, and is not intended to be initiated by friction in ammunition items. Formerly, extensively used as a military propellant, but now its military use is almost exclusively in propellant igniters and primers, in fuzes to give short delay, in powder-train time fuzes, in blank ammunition, and as spotting charges in practice ammunition.

blast. The brief and rapid changes in air pressure, density, temperature, and particle velocity resulting from the detonation of any explosive matter.

blast contour. A graphical representation of the results of tests of bare explosive charges against a given target structure. The contour represents the maximum distance from the center of detonation at

which some level of damage. *See:* **damage categories,** to the structure would occur, from charges of a certain weight, and in a given orientation. A given blast contour applies to only one target structure.

blast wave. *See:* **shock wave.** The shock wave transmitted through the air as the result of an explosion. Through usage, the term shock wave often is referred to as a blast wave, or air blast.

body armor. *See:* **armor, body, fragmentation protective.**

bomb. 1. In a broad sense, an explosive or other lethal agent, together with its container or holder, which is planted or thrown by hand, dropped from an aircraft, or projected by some other slow-speed device (as by lobbing it from a mortar), and is used to destroy, damage, injure, or kill. **2.** Anything similar to this object in appearance, operation, or effect, as a leaflet bomb, smoke bomb, photoflash bomb, a bomb-like container or chamber, etc.

bomb, atomic. (A-bomb) Meaning formerly limited to a bomb in which the explosive consists of a nuclear-fissionable, radioactive material, as uranium 235 or plutonium 239. Now accepted as synonymous with the term bomb, nuclear.

bomb, cobalt. A theoretical atomic or hydrogen bomb encased in cobalt, the cobalt of which would be transformed into deadly radioactive dust upon detonation.

bomb, hydrogen. (H-bomb) A fusion bomb in which an isotope of hydrogen is made to fuse under intense heat, with a resultant loss of weight and release of energy.

bomb, nuclear. A bomb that releases explosive energy either through nuclear fission or nuclear fusion. This term is applied either to the atomic bomb or the hydrogen bomb.

booster. Assembly of metal parts and explosive charge provided to augment the explosive component of a fuze, to cause detonation of the main explosive charge of the munition. May be an integral part of the fuze. The explosive in the booster must be sufficiently sensitive to be actuated by the small explosive elements in a fuze, and powerful enough to cause detonation of the main explosive filling.

brisance. The ability of an explosive to shatter the medium which confines it; the shattering effect of the explosive. (Adjective: brisant.)

bullet, incendiary. A bullet having an incendiary charge, used especially against flammable targets.

C

calorimetric test. As applied to interior ballistics, the use of a calorimeter to determine the thermochemical characteristics of propellants and explosives. The properties normally determined are heat of combustion, heat of explosion, heat of formation, and heat of reaction.

casualty agent. A toxic or lethal chemical agent that can be used effectively in the field.

casualty criteria. Standards by means of which may be classified the ability of ammunition items, or fragments therefrom, to inflict disabling wounds on personnel.

casualty gas. War gas capable of producing serious injury or death when used in effective concentrations.

CEP (*abbr.*) Circular probable error. The original expression appears to have been circular error probability.

chaff, countermeasures. A thin, flat, piece of metal foil, plain or backed, specifically designed to act as a countermeasure against enemy radar when released into the atmosphere.

Chapman-Jouguet plane. For a hypothetical, infinite-plane detonation wave: A moving reference plane, behind the initial shock front, in which it is variously assumed that: (a) reaction (and energy releases) has been effectively completed; (b) reaction product gases have reached thermodynamic equilibrium; (c) reaction gases, streaming backward out of the detonation, have reached such a condition that a forward-moving soundwave located at this

precise plane would remain a fixed distance behind the initial shock.

charge. **1.** A given quantity of explosive either by itself, or contained in a bomb, projectile, mine, or the like, or used as the propellant for a bullet or projectile. **2.** That with which a bomb, projectile, mine, or the like is filled, as a charge of explosive, thermite, etc. Also called the "fill," "filler," or "filling." **3.** In small arms, a cartridge or round of ammunition. **4.** To fill with a charge. **5.** To place a charge in a gun chamber.

charge, bare. An explosive charge without casing, prepared for use in determining explosive blast characteristics.

charge, bursting. The main explosive charge in a mine, bomb, projectile, or the like that breaks the casing and produces fragmentation or demolition.

charge, cased. **1.** Propelling charge within a cartridge case. **2.** Any explosive charge within a case, as opposed to a bare charge.

charge, shaped. (SC) An explosive charge with a shaped cavity. Sometimes called cavity charge. Called hollow charge in Great Britain. Use of the term shaped charge generally implies the presence of a lined cavity.

chemical agent. *military.* A chemical item either solid, liquid, or gas divided into three principal categories: war gases, smokes, and incendiaries. It is developed for the purpose of conducting defensive and/or offensive warfare. Through its chemical properties it produces: lethal, injurious, or irritant effects resulting in casualties; a screening or colored smoke; or acts as an incendiary agent.

chronograph. **1.** *general.* An instrument for measuring time. **2.** As applied to ballistics, an instrument for determining velocity by measuring the time required for a projectile to travel a known distance, thus furnishing the data for determination of the velocity. A complete chronograph usually consists of two main systems: one for detecting the projectile as it passes two (or more) points whose distance apart and distance from the muzzle are known accurately; and a second system for recording these passages on a time scale, thus supplying information that is readily converted into velocity. The velocity obtained in this manner is the average velocity between the recorded points. This is converted to muzzle velocity by adding to it the velocity lost, which is obtained from tables or charts which take into account the form factor (shape) of the projectile and the distance which it has traveled.

circular error. **1.** A bombing error measured by the radial distance of a point of bomb impact, or mean-point of impact, from the center of the target, excluding gross errors. **2.** With an airburst atomic bomb, this is the bombing error measured from the point on the ground, immediately below the bomb burst, to the desired ground zero. *See:* **ground zero.**

circular probable error. (CEP) **1.** The probable bombing error expressed in terms of the radius of a circle centered on the desired mean point of impact (DMPI) of a bombfall, and containing half of the expected bombfall, excluding gross errors; also sometimes applied to the actual bombing error. **2.** With an airburst atomic bomb, this is the probable bombing error expressed in terms of the radius of a circle centered upon the desired ground zero (DGZ), the radius from that point being projected horizontally to the point below the bomb burst. Gross errors are also excluded in atomic bombing. **3.** With reference to guided missiles, this is a probable error expressed in terms of the radius of a circle within which one-half of a given number of missiles can be expected to fall. Gross errors are usually excluded. *See:* **CEP.**

cobalt bomb. *See:* **bomb, cobalt.**

complete penetration. **1.** In Army terminology, penetration obtained when the projectile in the target, or light through the target, can be seen from the rear of the target. **2.** In Navy terminology, penetra-

tion obtained when the projectile passes through the target intact, or a major portion of the projectile passes through. 3. Protection complete penetration (which see).

controls. A general term applied to the means provided to enable the pilot to control the speed, direction of flight, attitude, power, etc., of an aircraft control surface.

control surface. 1. In a broad sense, any movable airfoil used to guide or control an aircraft, guided missile, or the like in the air, including the rudder, elevators, ailerons, spoiler flaps, trim tabs, and the like. 2. In restricted usage, one of the main control surfaces; i.e., the rudder, an elevator, or an aileron.

cover function. A function of the presented area of a target, based upon the shielding or cover afforded the target by the surrounding terrain.

critical mass. The minimum mass of a fissionable material, when related to a specific shape and environment, necessary to sustain a nuclear chain reaction.

D

damage. (dam.) 1. An injury short of complete destruction inflicted upon persons, equipment, or installations. 2. To cause damage, sense 1. 3. *See:* **damage categories.**

damage assessment. The result of examination of combat materiel, particularly aircraft and armored vehicles, after a simulated attack, to determine the category in which the damage resulting from the attack would be placed. *See:* **damage categories.** By the assessment, the individual or team making the examination, determine as accurately as possible the probability, in percentage points, that the inflicted damage would produce a result corresponding to a certain damage category.

damage categories. Two damage category classifications, applying to combat materiel subject to attack, have been accepted for use in evaluation damage and damage potential of ammunition. The first classification, applied to aircraft, employs the following damage evaluation terms:

K damage—damage such that the aircraft will fall out of control immediately after the damage occurs.

KK damage—damage such that the aircraft will disintegrate immediately after the damage occurs.

A damage—damage such that the aircraft will fall out of control within five minutes after damage occurs.

B damage—damage such that the aircraft will be unable to return to its base.

C damage—damage that will prevent the aircraft from completing its mission. The second classification, applied to armored vehicles, employs the following damage evaluation terms:

K damage—damage that will cause the vehicle to be destroyed.

F damage—damage causing complete or partial loss of the ability of the vehicle to fire its main armament and machine guns.

M damage—damage causing immobilization of the vehicle.

damage radius. 1. The distance at which, in terms of experience or theoretical calculations, certain types of damage can be expected from a specified type of explosive item. 2. Atomic explosion—the distance from ground zero at which there is a 50 percent probability that a target element susceptible to the weapon effect considered will be damaged.

decay. The spontaneous disintegration of radioactive nuclei to a more stable form, generally accomplished by the emission of particles and/or gamma radiation. Decay also refers to the decrease in intensity of radioactivity with passage of time.

decay factor. A constant which is multiplied by the value of dose rate at one hour, to give the rate at some other time.

desired ground zero. (DGZ) For a surface burst, the point on the earth's surface where atomic detonation is desired. For

an air burst or underground burst, the point is on the earth's surface directly below or directly above the desired point of detonation.

detonation. An exothermic chemical reaction that propagates with such rapidity, that the rate of advance of the reaction zone into the unreacted material exceeds the velocity of sound in the unreacted material; that is, the advancing reaction zone is preceded by a shock wave. A detonation is classed as an explosion. The rate of advance of the reaction zone is termed detonation rate or detonation velocity. When this rate of advance attains such a value that it will continue without diminution through the unreacted material, it is termed the stable detonation velocity. The exact value of this term is dependent upon a number of factors, principally the chemical and physical properties of the material. When the detonation rate is equal to or greater than the stable detonation velocity of the explosive, the reaction is termed a high-order detonation. When the detonation rate is lower than the stable detonation velocity of the explosive, the reaction is termed a low-order detonation.

detonation front. The reaction zone of a detonation.

detonation wave. The shock wave which precedes the advancing reaction zone in a high-order detonation.

detonator. An explosive train component which can be activated by either a nonexplosive impulse, or the action of a primer, and is capable of reliably initiating high-order detonation in a subsequent, high-explosive component of train. When activated by a nonexplosive impulse, a detonator includes the function of a primer. In general, detonators are classified in accordance with the method of initiation, such as percussion, stab, electric, flash, etc.

DGZ (*abbr.*) Desired ground zero.

discarding petal. A part of a discarding sabot in which the sabot is composed of a base and attached pieces extending from it. These pieces, called petals, surround the core. They peel back under centrifugal and aerodynamic forces and are discarded just in front of a gun muzzle.

discarding sabot. *See:* **sabot.**

dose. The total amount of nuclear radiation received by an individual, expressed in roentgens. Usually used to mean total dose. Also expressed as RAD (which see).

dose rate. A measurement of the intensity of persistent or residual radio-activity expressed in terms of roentgens per hour. Also expressed as RAD.

drag force or component. (stress analysis) A force or component, in the drag direction; i.e., parallel to the relative wind.

dynamic pressure. *See:* **pressure, dynamic.**

dynamics. A branch of mechanics that treats of the motion of bodies, and of the forces acting upon bodies in motion or in process of changing motion.

dynamite. A high explosive, consisting of nitroglycerin and/or nitroglycol and/or ammonium nitrate and other materials with or without an inert base, packed in cylindrical paper cartridges or in bags. It is set off by a detonator and is generally used to break rocks, move dirt, or demolish buildings.

E

electronic countermeasures. (ECM) Usually pl. Any of various offensive or defensive tactics using electronic and reflection devices to reduce the military effectiveness of enemy equipment, or tactics, employing or affected by electromagnetic radiations.

electronic jamming. An action involved in electronic countermeasures, being the radiation or re-radiation of electromagnetic waves to impair the use of a specific segment of the radio spectrum. Usually shortened to "jamming."

energy, radiant. Energy consisting of electromagnetic waves, such as light, infrared, radio, and radar.

explosion. (explo) **1.** A chemical reaction or change of state, effect in an exceed-

ingly short space of time, with the generation of a high temperature and, generally, a large quantity of gas. An explosion produces a shock wave in the surrounding medium. **2.** Now also used with reference to the explosive effects of nuclear weapons. **3.** In general sense, any violent bursting or expansion, with noise, following a sudden production of great pressure or a release of great pressure.

explosion, chemical. *See:* **explosion, sense 1.**

explosive. (explo) **1.** A substance or mixture of substances which may be made to undergo a rapid chemical change, without an outside supply of oxygen, with the liberation of large quantities of energy, generally accompanied by the evolution of hot gases. Explosives are divided into two classes, high explosives, and low explosives, according to their rate of reaction in normal usage. Certain mixtures of fuels and oxidizers that can be made to explode are considered to be explosives. However, a substance such as a fuel which requires an outside source of oxidizer to explode, or an oxidizer which requires an outside source of fuel to explode, is not considered an explosive. 2. Now used loosely with reference to nuclear weapons.

explosive, conventional. A nonatomic explosive.

F

fallback. That part of the material carried into the air by an atomic explosion that ultimately drops back to the earth, or water, at the site of the explosion.

fallout. The process of precipitation to earth of particulate matter from an atomic cloud; also applied in a collective sense to the particulate matter itself. Although not necessarily so, such particulate matter is generally radioactive.

fallout area. The area on which radioactive materials have settled out, or the area on which it is predicted from weather conditions that radioactive materials may settle out.

film badge. A photographic film packet to to be carried by personnel, in the form of a badge, for measuring and permanently recording (usually) gamma ray dosage.

fin stabilization. Method of stabilizing a projectile, as a rocket bomb or missile, during flight, by the aerodynamic use of protruding fins.

fission. Of radioactive material: To split apart within the atomic nucleus, as in, "cobalt would neither fission nor fuse."

fissionable. Of a material such as uranium: Subject to nuclear fission.

fission bomb. A bomb intended to derive its explosive force from nuclear fission. *See:* **bomb, atomic.**

fission, nuclear. The splitting of an atomic nucleus, as by neutron bombardment. *See:* **bomb, atomic.**

flash radiography. Method of high-speed, X-ray photography. Used in analysis of ammunition functioning.

flechette. 1. An aerial dart. 2. A small fin-stabilized missile, a large number of which can be loaded in artillery canister.

flutter. A vibrating and oscillating movement of a wing, control surface, or the like, caused by aerodynamic forces acting upon an airfoil or surface having elastic and inertial qualities.

form factor. Factor introduced into the ballistic coefficient of a projectile, based on the shape of the projectile. Sometimes called "coefficient of form." *See:* **ballistic coefficient.**

fragment. (frag) 1. A piece of an exploding or exploded bomb, projectile, or the like. 2. To break into fragments.

fragmentation. (frag) A term applied to ammunition, indicating that the item is primarily intended to produce a fragmentation effect.

fragmentation test. Test conducted to determine the number and weight distribution, and where the method used permits, the

velocity and spatial distribution, of the fragments produced by a projectile or other munition upon detonation. Recovery of fragments, without determination of velocity or spatial distribution, can be accomplished by fragmenting in sand or sawdust, or over water. Determination of velocity and spatial distribution requires elaborate recovery means and instrumentation.

fragment density distribution. The number of fragments per unit solid angle (steradian).

fragment mass distribution. Spectrum of fragment weights produced by a shell or warhead.

fuse. (not to be confused with the term fuze) **1.** An igniting or explosive device in the form of a cord, consisting of a flexible fabric tube and a core of low or high explosive. Used in blasting and demolition work, and in certain munitions. Fuse with black powder or other low explosive core is called: fuse, blasting, time. Fuse with PETN or other high explosive core is called: cord, detonating. **2.** An electrical fuse.

fuselage. The body, of approximately streamline form, of an aircraft or missile. It is the part to which the tail unit and wings (if included) are attached.

fusion. **1.** *atomic energy.* Fusion, nuclear. **2.** *optics.* The mental blending of the right and left eye images into a single, clear image by stereoscopic action.

fusion, nuclear. The fusing or uniting of the atomic nuclei of an isotope, as those of deuterium, to form other nuclei under the influence of intense heat. *See:* **bomb, hydrogen.**

fuze. **1.** A device with explosive components designed to initiate a train of fire or detonation in an item of ammunition, by an action such as hydrostatic pressure, electrical energy, chemical action, impact, mechanical time, or a combination of these. Excludes: fuse (as modified). **2.** A non-explosive device designed to actuate another component by atmospheric pressure and/or temperature change, electrical energy, chemical action, physical impact, acceleration and/or deceleration forces, electromagnetic waves or pulses, and external forces. **3.** To equip an item of ammunition with a fuze.

G

gain. **1.** *radio.* In an amplifying system. the increase of output power, voltage, or current over the input power, voltage, or current, expressed in terms of a ratio. **2.** *radar.* The difference, expressed as a ratio, between the power radiated by a directional antenna and the power radiated by an isotropic antenna, when both have an equal power output.

gelatin block. A block of transparent gelatin, the consistency of which is approximately similar to human tissue. It is used to compare the lethality of bullets, fragments, and flechettes.

Geneva Convention. An international agreement dealing with the humane treatment of combatants and noncombatants in time of war. The original Convention, signed at Geneva in 1864, concerned wounded soldiers and prisoners of war. Later amendments and revisions extended the provisions to victims of maritime actions and to civilian populations. In 1949 existing provisions were reformulated into four conventions for the protection of war victims. The U. S. has been a signatory of the successive conventions, and since 1864 the Convention has been the charter of the International Red Cross.

grenade. A small exposive or chemical missile, originally designed to be thrown by hand, but now also designed to be projected from special grenade launchers, usually fitted to rifles or carbines. Grenades may be classified in a broad sense as: grenade, hand; and grenade, rifle. Many varieties and variations of these have been used, including a number of improvised ones.

ground zero (GZ). The point on the earth's surface at which, above which, or below

which, an atomic detonation has actually occurred.

guided missile. An unmanned self-propelled vehicle, with or without a warhead, designed to move in a trajectory or flight path all or partially above the earth's surface, and whose trajectory or course, while in flight, is capable of being controlled remotely, or by homing systems, or by inertial and/or programmed guidance from within. Excludes drones, torpedos, and rockets and other vehicles whose trajectory or course cannot be controlled while in flight.

gun. 1. *General.* A piece of ordnance consisting essentially of a tube or barrel, for throwing projectiles by force, usually the force of an explosive, but sometimes that of compressed gas, spring, etc. The general term embraces such weapons as are sometimes specifically designated as gun, howitzer, mortar, cannon, firearm, rifle, shotgun, carbine, pistol, revolver. 2. *Specif.* A gun with relatively long barrel, usually over 30 calibers, with relatively high initial velocity, and capable of being fired at low angles of elevation.

Gurney constant. A factor for use in Gurney formulas, which is constant for each explosive, but which varies with different explosives. It is expressed in feet per second. *See:* **Gurney formulas.**

Gurney formulas. A series of formulas, each formula corresponding to a particular geometry of the container, which enables quite accurate prediction of the initial fragment velocity. The velocity is dependent on the geometry, the explosive used, and the ratio of the explosive charge and metal weights.

GZ (*abbr.*). Ground Zero.

H

HE (*abbr.*). High explosive.

HEAT, HE, AT (*abbr.*). (often pronounced as a word) Originally an abbreviation for high explosive antitank. A term used to designate high explosive ammunition containing a shaped charge. *See:* **charge, shaped.**

HEP (*abbr.*). (often pronounced as a word) An abbreviation for high-explosive plastic, sometimes called a "squash charge". A term used to designate ammunition (usually used against tanks and reinforced structures) which resembles an ordinary HE shell, but the explosive component is a plastic explosive. This plastic deforms on impact, resulting in an intimate contact of the explosive with the target surface, thereby causing much greater shock waves than other types of explosives, resulting in spalling of the opposite surface.

high explosive. (HE) An explosive which, when used in its normal manner, detonates rather than deflagrating or burning; that is, the rate of advance of the reaction zone into the unreacted material exceeds the velocity of sound in the unreacted material. Whether an explosive reacts as a high explosive or as a low explosive depends on the manner in which it is initiated and confined. For example, a double-base propellant when initiated in the usual manner is a low explosive. However, this material can be made to detonate if the propellant is initiated by an intense shock. Conversely, a high explosive like TNT, under certain conditions, can be ignited by flame and will burn without detonating. High explosives are divided into two classes: primary high explosives and secondary high explosives, according to their sensitivity to heat and shock.

high-order detonation. *See:* **detonation.**

I

illuminant composition. A mixture of materials suitable for use in the candle of a pyrotechnic device, having production of high intensity light as its principal function. The materials used include a fuel (reducing agent), an oxidizing agent, and a binder, plus color intensifier and waterproofing agent. The mixture is loaded

under pressure in a container to form the illuminant candle.

illuminating. Indicates, in ammunition nomenclature, that the munition is intended primarily for iluminating purposes. Usually contains a flare, and may contain a parachute for suspension in the air.

impulse. A vector quantity defined by the time integral of the force F acting on a particle over a finite interval,

for example, $\int_{t_1}^{t_2} F dt$

for the interval from t_1 to t_2.

Specifically, with respect to blast waves, "impulse" refers to the time integral of pressure.

initial radiation. The nuclear radiation accompanying an atomic explosion and emitted from the resultant fireball; immediate radiation. It includes the neutrons and gamma rays given off at the instant of the explosion, and the alpha, beta, and gamma rays emitted in the rising fireball and the column of smoke. In contrast to residual radiation, its delivery to persons and objects on the earth's surface is terminated by the removal of the source (fission products in the atomic cloud), from within effective radiation range of the earth, by the rising cloud.

J

jam. **1.** Of a machine gun, full-automatic, semiautomatic or other firearm: To stick or become inoperative because of improper loading, ejection, or the like. **2.** To make the transmissions of a radio unintelligible; to make a radio or radar set ineffective, either by the use of counter-transmissions or by the use of a confusion reflector. *See:* **electronic jamming.**

jet. **1.** As pertains to shaped charge ammunition: **a.** From a lined charge: The slender, generally fastest-moving part of a liner after collapse. **b.** From an unlined shaped charge: The central stream of high-velocity gases produced upon detonation. **2.** A jet engine. **3.** A jet airplane

jet breakup. As pertains to shaped charge ammunition: Breaking of jet into discrete particles. The time of breakup is a factor in effective penetration. Bifurcation: radial breakup of the jet into two distinct jets. Polyfurcation: radial breakup of the jet resulting in three or more distinct jets.

K

Kelvin scale. (K) A temperature scale that uses centigrade degrees, but makes the zero degree signify absolute zero. In this scale, water freezes at plus 273.16 degrees and boils at 373.16 degrees. This scale is named after the first Baron Kelvin (1824-1907), an English mathematical physcist.

kiloton. (KT) Refers to the energy released of a thousand tons of TNT, where 1 ton equals 2,000 pounds, and where the energy content of TNT is defined as 1,100 calories/gram.

kinetic energy ammunition. Ammunition designed to inflict damage to fortifications, armored vehicles, or ships by reason of the kinetic energy of the missile upon impact. The damage may consist of shattering, spalling (which see), or piercing. The missile may be solid, or may contain an explosive charge intended to function after penetration.

Kirkwood-Brinkley's theory. In terminal ballistics, a theory formulating the scaling laws from which the effect of blast at high altitudes may be inferred, based upon observed results at ground level. *See:* **scaling law, and Sach's theory.**

L

lethal area. In terminal ballistics, a figure of merit, having the dimension of area, which permits prediction of the number of casualties a missile may be expected to produce when employed under specified conditions. An equation has been evolved stating the relationship between the lethal area and the numerous factors affecting its numerical value.

lethality criteria. *See:* **casualty criteria.**

low-order detonation. *See:* **detonation.**

M

Mach front. A Mach stem.

Mach stem. A shock wave or front formed above the surface of the earth by the fusion of direct and reflected shock waves resulting from an airburst bomb. Also called "Mach wave" and "Mach front."

megaton. (MT) Refers to the energy release of a million tons of TNT (10^{15} calories).

Mev (*abbr.*). Million electron-volts. Sometimes abbr. MEV.

mine. **1.** An encased explosive or chemical charge designed to be placed in position so that it detonates when its target touches it, or moves near it, or when touched-off by remote control. General types are: land mine, and underwater mine. **2.** An explosive charge placed in a subterranean tunnel under a fortification. **3.** To place mines or prepared charges.

missile (msl). **1.** Any object that is, or is designed to be, thrown, dropped, projected, or propelled, for the purpose of making it strike a target. **2.** A guided missile (which see). **3.** A ballistic missile (which see).

Misznay-Schardin effect. The acceleration of a solid end-plate (usually metal) from the face of an explosive charge under detonation, such that the end-plate remains a solid and is usable as a missile.

monocoque. A type of airplane construction in which the skin of the fuselage bears the primary stresses arising in the fuselage.

N

Napalm. (NP) **1.** Aluminum soap in powder form, used to gelatinize oil or gasoline for use in Napalm bombs or flame throwers. **2.** The resultant, gelatinized substance.

nuclear energy. Energy held within the nucleus of an atom, released in part in certain other elements by the process of nuclear fusion. In the restrictive sense, that part of this energy that is released by fission or fusion. In nuclear fission, the energy released comes from the atomic nucleus being split, resulting in the emission of nuclear particles, such as neutrons, the alpha particle, or the beta particle. In nuclear fusion, the combining atomic nuclei fail to utilize their entire atomic mass in forming the new nucleus, the unused mass being converted into energy.

nuclear fission. *See:* **fission, nuclear.**

nuclear fusion. *See:* **fusion, nuclear.**

nuclear weapon. A bomb, projectile, missile, or the like that carries a nuclear warhead. Also, the warhead itself.

O

ogive. The curved or tapered front of a projectile. As a geometrical body, a convex solid of revolution in which the generating area is bounded by an arc of a circle, the center of which lies on the side of the axis of revolution opposite to the arc. When applied to a projectile contour, the radius of the arc is expressed in calibers, such as a "7-caliber ogive." With a bullet, bomb, or other projectile having a fuze forming the nose, the ogive is included between a point where the projectile begins to curve, or taper, and a point on the line where fuze and body meet. In other types of projectiles, the nose of the projectile is included as a part of the ogive.

Ordnance Proof Manual. (OPM) A manual whose purpose is to simplify, codify, and standardize proof technique and to provide a guide for those who plan, execute, or analyze proof work on ordnance materiel. The manual includes a discussion, in detail, of basic principles, related facts, and specific instructions relating to: classification of tests; examples of test programs on all classes or types of ordnance materiel; proof technique, including the detail operation of proof facilities; the methods of reductions of proof data, calculations performed, the evaluation of tests, and instructions for preparation of proof reports.

overmatching plate. Armor plate whose thickness exceeds the diameter of the projectile.

overmatching projectile. A projectile whose diameter exceeds the thickness of the armor plate.

P

partial penetration. Penetration obtained when a projectile fails to pass through the target far enough for either the projectile itself, or light from its penetration, to be seen from the back of the target; Army partial penetration. *See:* **complete penetration, protection complete penetration.**

passive armor. A protective device against shaped charge ammunition. Designed to absorb the energy of a shaped charge. Examples: spaced armor, homogeneous materials, plastic armors, composite designs.

peak overpressure. The highest overpressure resulting from the blast wave. Peak overpressures near the fireball of an atomic explosion are very high, but drop off rapidly as the blast wave travels along the ground outward from ground zero.

penumbra. The space of partial illumination, as in an eclipse, between the umbra (perfect shadow) and the full light.

piezoelectric. The property of certain crystals to develop electrical charge or potential difference across certain crystal faces, when subjected to a strain by mechanical forces or, conversely, to produce a mechanical force when a voltage is applied across the material. Examples of piezoelectric materials are quartz, tourmaline, Rochelle salts, and barium titanate.

pitch. An angular displacement about an axis parallel to the lateral axis of an airframe or vehicle.

presented area. That area of a target normal to the flight path of a projectile.

pressure, dynamic. The pressure exerted by a gas, liquid, or solid solely by virtue of its relative motion when it strikes an object. For example, in a pitot-static tube, dynamic pressure is that part of the impact pressure derived from the relative motion of the air, as distinguished from that derived from atmospheric pressure.

primary blast injuries. Those injuries incurred as a direct result of the pressures of the blast or shock wave.

projectile. (proj) 1. *General.* A body projected by exterior force and continuing in motion by its own inertia. 2. *Specif.* A missile (which see) for use in any type of gun (which see). In the general sense, the term is sometimes applied to rockets and guided missiles, although they may not fall within the stated definition. In sense 2, the term projectile is preferred over shell, shot, and the like, in official nomenclature.

projectile, arrow. A relatively long projectile which is designed to be fired from a gun of a caliber considerably larger than the diameter of the projectile body. It is stabilized by fins having a span approximately that of a caliber of the gun. This design is made for the purpose of increasing the velocity, to decrease the time of flight, and/or increase the striking energy of the projectile.

protection complete penetration. Penetration in which a fragment or fragments of either the impacting projectile or the plate are thrown to the rear of the plate with sufficient energy to perforate a .020-inch aluminum-alloy, 24ST, sheet, or its equivalent, when placed so as to receive those fragments passing from the rear of the plate. The "Protection Criterion." When it is possible to observe that these conditions are being met without the use of the sheet, as in heavier plate testing, the sheet may be omitted.

protection partial penetration. Penetration which approaches but does not fulfill the requirements for protection complete penetration.

R

RAD. (from radiation absorbed dose) A unit of absorbed dose of ionizing radiation. The RAD, 100 ergs/gram, is a measure of the energy imparted to matter by ionizing radiation, per unit mass of irradiated material, at the place of interest.

radiation. **1.** The transmission of energy through space in the form of electronic waves. 2. Nuclear radiation.

radiation absorbed dose (dosage). (RAD) The total quantity of ionizing radiation absorbed by an individual or any mass of material exposed to radiation. If the radiation is X, or gamma, and the mass is free air, the unit of measure is the roentgen.

radiation dosage. Total quantity of radiation to which a person is exposed over a period of time. It is measured in roentgens.

radiation dose rate. The radiation dose (dosage) absorbed per unit time. The common unit of measure for X or gamma radiation is roentgen or milliroentgen per hour.

radiation intensity. The amount of radiant energy, per unit time, passing through a unit area perpendicular to the line of propagation, at the point in question. This term is often used incorrectly when dose rate is intended.

radiography. Nondestructive examination of matter by means of X-rays or gamma rays. The rays are permitted to impinge on a fluorescent screen for temporary work, or photographic film for permanent record. Used in metal industry, research, and analysis, for purposes such as determining the soundness of castings and welded joints.

radiological warfare. The employment of agents or weapons to produce residual radioactive contamination, as distinguished from the initial effects of a nuclear explosion (blast, thermal, and initial nuclear radiation).

Rankine scale. (R) A thermometer scale which uses Fahrenheit degrees, with zero as absolute zero of the Fahrenheit scale. The freezing point of water is 491.69 degrees.

rarefaction. In an atomic bomb explosion, a condition existing at the center of the explosion, in which the pressure, after a rise induced by the explosion, drops below that which existed prior to the explosion.

rarefaction wave. A pressure wave, or rush of air or water, induced by rarefaction. The rarefaction wave (also called a suction wave) travels in the opposite direction to that of the shock wave directly following the explosion.

raster. A system of luminescent lines traced on the phosphor of a cathode-ray tube by motion of the cathode-ray beam. The changes of brightness in the lines produce a picture as a television picture or a radar map. This word is of German origin and is used particularly in television.

REM (*abbr.*). Roentgen equivalent mammal.

residual radiation. Nuclear radiation emitted by the radioactive material deposited after an atomic burst, or after an attack with radiological warfare agents. Following an atomic burst, the radioactive residue is in the form of fission products, unfissioned nuclear material, and material, such as earth, water, and exposed equipment, in which radioactivity may have been induced by neutron bombardment.

rocket. An unmanned, self-propelled vehicle with or without a warhead, designed to travel above the surface of the earth, and whose trajectory or course, while in flight, cannot be controlled. Excludes guided missile and other vehicles whose trajectory or course, while in flight, can be controlled remotely, or by homing systems, or by inertial and/or programmed guidance from within.

roentgen. A measure of ionization produced by X-ray or gamma radiation. The unit of measurement of radiation in terms of its effect on human beings. This is technically defined as the amount of X or gamma radiation which as a result of ionization will produce, in 1 cubic centimeter of dry air at standard conditions of temperature and pressure, ions carrying 1 electrostatic unit of electricity of either sign.

roentgen equivalent mammal. (REM) The quantity of any type of ionizing radiation which, when absorbed by a mammal, produces an effective equivalent to the ab-

sorption by the mammal of one roentgen of X or gamma radiation.

roll. An angular displacement about an axis parallel to the longitudinal axis of an airframe or a missile.

S

sabot. Lightweight carrier in which a subcaliber projectile is centered to permit firing the projectile in the larger caliber weapon. The sabot diameter fills the bore of the weapon from which the projectile is fired. One type of sabot, discarded a short distance from the muzzle, is known as a "discarding sabot." A sabot is used with a high velocity armor-piercing projectile having a tungsten carbide core; in this case, the core may be considered as the subcaliber projectile.

Sach's theory. An alternate theory to Kirkwood-Brinkley's theory, embodying scaling laws by which the effect of blast at high altitudes may be inferred from the results at ground level.

scaling law. A formula which permits the calculation of some property for a given article based on data obtained from a similar, but different size, article; e.g., crater size, nuclear radiation, etc., for a nuclear warhead of any yield, from the known values for another yield.

secondary blast injuries. Those injuries sustained from the indirect effects of a blast; such as falling rubble from a collapsed building, or missiles (debris or objects) which have been picked up by the blast winds generated and hurled against an individual. Also includes injuries resulting from individuals being hurled against stationary objects.

shock resistance. Armor. That property which prevents cracking or general rupture when impacted by fragments, irregular projectiles, or glancing blows from overmatching projectiles. *See:* **shock test.**

shock test. Armor plate. The test to determine if the armor will fail under impacts of overmatching projectiles. Also called ballistic shock test.

shock wave. The steep, frontal compression, or pressure discontinuity, rapidly advancing through a medium as the consequence of a sudden application of pressure to the medium. Its form depends on the magnitude of the pressure, and the displacement of the medium, as the wave progresses. In soil, the shock wave is commonly referred to as the ground shock; in water, the water shock; and in air, the air blast or blast wave.

shock wave, reflected. A shock wave resulting from an explosion, especially from the explosion of an airburst bomb, which is reflected from a surface or object.

shot. 1.a. A solid projectile for cannon, without a bursting charge. **b.** A mass or load of numerous, relatively small, lead pellets used in a shotgun, as birdshot or buckshot. 2. That which is fired from a gun as "the first shot was over the target." In sense **1.a.,** the term "projectile" is preferred for uniformity in nomenclature.

side spray. Fragments of a bursting projectile thrown sidewise from the line of flight, in contrast with base spray, thrown to the rear, and nose spray, thrown to the front.

skirting armor. *See:* **skirting plate, spaced armor.**

skirting plate. A thin plate, which is spaced a considerable distance in front of the main armor plate and which acts as a passive form of resistance to the jet of shaped charge ammunition.

spaced armor. An arrangement of armor plate, using two or more thicknesses, each thickness spaced from the adjoining one. Used as protective device, particularly against shaped charge ammunition.

spall. Fragment(s) torn from either surface of armor plate, such as might result from the impact of kinetic energy ammunition or the functioning of shaped charge ammunition.

spalling. Production of a spall(s).

spall resistance. That property of armor which prevents the armor from projecting spalls into the armored vehicle when struck by a projectile.

spar. Any principal structural member in an airfoil; esp. in a wing, running from tip to tip or from root to tip.

spectroscope. An optical instrument designed to break up the light from a source into its constituent wave lengths for the observation of spectra, thus providing a means of qualitative or quantitative study of the spectrum formed. The instrument essentially consists of a slit, a lens system, a dispersion system, and an observation system.

spin stabilization. Method of stabilizing a projectile during flight by causing it to rotate about its own longitudinal axis.

stabilizer. Any airfoil, or any combination of airfoils considered as a single unit, the primary function of which is to give stability to an aircraft or missile.

Standard Atmosphere. Since the resistance of the air to a projectile depends upon the wind, the density, and the temperature, it is convenient to assume, as a point of departure in computing firing tables, a wind, density and temperature structure for this purpose. A sort of average or representative air structure so derived is called "a standard atmosphere." The standard atmosphere for the United States Armed Services is the U. S. Standard Atmosphere, which is that of the International Civil Aviation Organization (ICAO). This standard atmosphere assumes a ground pressure of 760 millimeters of mercury and a ground temperature of 15° C. The temperature throughout the troposphere, that is, the region where turbulent mixing takes place, extending up to 11 kilometer, is given by the formula

$$\text{absolute temperature } T\ (^\circ K) = 288.16 - 6.5\,H$$

where H is the height above sea level measured in kilometers. In the stratosphere, extending from 11 kilometers to 25 kilometers, the temperature is assumed to be a constant 216.66° K. Above the stratosphere, other laws are assumed. Although the ICAO atmosphere makes no assumptions about wind structure, for firing table purposes it is assumed that there is no wind.

standard deviation. In the field of testing, a measure of the deviation of the individual values of a series from their mean value. The standard deviation is expressed algebraically by the formula

$$\sqrt{\frac{\Sigma x^2}{N}}$$

where Σ (sigma) means the sum of, x equals the deviation from the mean, and N equals the number of scores or individuals in the distribution. For example, let us assume a distribution of 5, with scores of 2, 4, 6, 8, and 10. The mean of these scores is 6, the deviations −4, −2, 0, +2, and +4. Each, squared, gives 16, 4, 0, 4, and 16. The sum of these is 40, which divided by 5 makes 8. The square root of 8 is 2.82. This is the standard deviation. Other methods of arriving at the standard deviation are used, but they go back to the formula shown.

standoff distance. The distance between the base of a shaped charge liner and the surface of a target.

T

terminal ballistics. The study of terminal ballistics is concerned with developing an understanding of the fundamental principles underlying the destructive effects of weapons on targets. Knowledge so gained is applied, offensively, to the improvement of various weapons systems, ranging from rifles and hand grenades carried by soldiers to nuclear warheads carried by ICBM's, and defensively, to the improvement of protective devices, such as body armor for soldiers, protective armor for ground, air-borne and space vehicles, and ground structures, permanent and tem-

porary. Both experimental and theoretical investigations are carried out in the fields of blast, detonation phenomena, penetration of fragments and bullets into various media under study, and ground shock, combustion, and nuclear radiation.

thermonuclear. Of or pertaining to nuclear reactions or processes caused by heat, esp. to nuclear fusion caused by the intense heat of an atomic bomb explosion. (*See:* fusion, nuclear.)

TNT. (*abbr*). Trinitrotoluene (trinitrotoluol). This explosive is better known by its abbreviation than by its chemical name. *See:* **trinitrotoluene.**

trinitrotoluene. (TNT) High explosive widely used as explosive filler in munitions and by engineers; trinitrotoluol; TNT.

tungsten carbide core. The heavy, hard core used in high-velocity armor-piercing type projectiles.

turbulence. A condition in the airflow about a wing, or other airfoil, in which different velocities and pressures are laterally mixed between layers of the airflow.

U

ultraviolet. Outside the visible spectrum, at the violet end; higher in frequency than visible light. The opposite of "infrared." Said of light, rays, frequencies; hence, "ultraviolet light."

V

vulnerable area. The product of: (1) the probability that a projectile striking a target will cause disabling damage; and (2) the presented area of the target.

W

war gas. Toxic or irritant chemical agent regardless of its physical state, whose properties may be effectively exploited in the field of war.

warhead. Rocket and guided missile: That portion which is the payload the vehicle is to deliver to a predetermined point in space and time. In a general sense, it includes the payload plus the missile section surrounding the payload, and its related components. In a specific sense, it refers to the payload only; in which case the complete missile payload assembly is called a warhead section. Warheads may be categorized as high explosive, chemical, nuclear, ballast, etc. In the case of nuclear warheads (sometimes referred to as special warheads), the term warhead refers to the nuclear weapon proper. This, along with the kit which adapts the nuclear weapon proper to the missile warhead application, and the missile warhead compartment, makes up the complete warhead section.

wave length. The distance traveled in one period or cycle by a periodic disturbance. It is the distance between corresponding phases of two consecutive waves of a wave train. A wave length is the quotient of velocity divided by frequency.

wave shaper. Pertaining to explosives, an insert or core of inert material, or of explosives having different detonation rates, used for changing the shape of the detonation wave.

wound ballistics. That portion of terminal ballistics specializing in the effect of bullets and fragments in wounding personnel, and in the factors producing disabling injuries. *See:* **casualty criteria.**

Y

yaw. 1. The angle between the direction of motion of a projectile and the axis of the projectile, referred to either as "yaw," or, more completely, as "angle of yaw." The angle of yaw increases with time of flight in an unstable projectile, and decreases to a constant value called the "yaw of repose," or the "repose angle of yaw," in a stable projectile. **2.** Angular displacement about an axis parallel to the normal axis of an aircraft, guided missile or the like.

yield. Also known as energy yield. The total

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effective energy released in a nuclear (or atomic) explosion. It is usually expressed in terms of the equivalent tonnage of TNT required to produce the same energy release in an explosion. The total energy yield is manifested as nuclear radiation, thermal radiation, and shock (or blast) energy; the actual distribution being dependent upon the medium in which the explosion occurs (primarily), and also upon the type of weapon and the time after detonation.

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PREFACE

Collection and Analysis of Data Concerning Targets, forming PART TWO of Elements of Terminal Ballistics, contains Chapters 5 through 8. It discusses the nature of terminal ballistics as it pertains to various types of targets, but primarily, it describes the methods and techniques which are used in the collection and analysis of data concerning these targets.

Chapters 5, 6, 7 and 8 treat the subjects of personnel, ground vehicles, ground structures, and aircraft, respectively, when considered as targets.

An index is included in this volume and a glossary in part one.

The other handbooks which, together with this volume, comprise Elements of Terminal Ballistics are:

AMCP 706–160 (S)	PART ONE, Introduction, Kill Mechanisms, and Vulnerability (U)
AMCP 706–162 (S–RD)	PART THREE, Application to Missile and Space Targets (U)

Chapter 5 (S)

PERSONNEL

Section I (U)—Introduction

5–1. SCOPE OF THE CHAPTER

This chapter covers the collection and analysis of data concerning the incapacitation and mortality of personnel due to the more important kill mechanisms. Among these are the terminal effectiveness of projectiles (specifically, fragments, bullets, and flechettes), blast, thermal radiation, nuclear radiation, and chemical and biological agents. Each of these is dealt with in a separate section.

5–2. CROSS-REFERENCE INFORMATION

The general discussion of personnel vulnerability is found in Ch. 3, Sec. I, and general discussions of each of the above listed kill mechanisms are found in separate sections of Ch. 2. These sections should be read for background information. Reference should also be made to the various sections of Ch. 4, each of which discusses the collection and analysis of data concerning a specific one of the kill mechanisms, as such.

Section II (S)—Fragments, Bullets, and Flechettes

5–3. (U) INTRODUCTION

In the discussion of the effects of fragments, bullets, and flechettes on personnel, the basic problem under consideration is the probability of a random hit incapacitating a soldier. Included in the discussion as significant factors are lethality criteria,,kill probability, presented area functions, effects of body armor, comparison of damage effects of projectile type, and lethal area considerations. A general discussion of incapacitation criteria is also to be found in Ch. 3, Sec. I, Par. 3–2.

5–4. (S) LETHALITY CRITERIA

5–4.1. (S) Experimental Procedure

Lethality criteria are developed from experimental investigations on test animals, and are correlated with human structure on a medical basis. Studies in this field are conducted by the Ordnance Corps at the Ballistic Research Laboratories (BRL), and systematic, experimental, wound-ballistic programs to supply data for the studies are carried out at the Biophysics Division of the Chemical Research and Development Laboratories (CRDL) of the Army Chemical Center. Limited experimental programs have been completed, and the provisional casualty criteria presently in use must necessarily change to conform to wound ballistics data as they become available.

The collection, interpretation, analysis, and synthesis of wound ballistics data is a relatively new undertaking. Much has been learned in recent years, and continued change and rapid advancement of knowledge is expected. Therefore, although the material presented here is currently accepted, it may be subject to extensive changes as new techniques are introduced. More consideration may be given in future studies to a closer relationship of basic experimental data to human functional disability, to man-task relationships, and to different interpretations of medical assessments of wound damage.

The method of collection of these data is as follows. Fragments of known material, shape,

mass, and striking velocity are fired from guns at animals (goats) and the wounds are carefully studied. Hits are obtained on all important regions and through all important body tissues. The wounds are medically and surgically analyzed. The rates of loss of velocity by similar fragments as they traverse known thicknesses of skin, muscle tissue, bone, and other types of body tissue are independently measured by special retardation experiments.

Using detailed anatomical drawings, the human body is divided conceptually into many lateral cross sections, upon which the consequences of hypothetical impacts by individual fragments are carefully and separately studied. For each position of fragment impact, the tissues and structures that would be hit are predicted, along with the remaining velocities of the fragment. From the nature of structures traversed, and from the remaining velocities along the path of the fragment, the severity of the wound that would result is predicted on the basis of the medical study of the test wounds as correlated to similar type wounds in a human. This is done for all areas of the body surface, for a number of horizontal impacts. (A very limited analysis of angular impacts is now in process.) In analyzing the time for incapacitation, the effect of the wound is related to the functioning of a soldier's extremities. The ability to see, hear, think, communicate and perform an assigned task is considered necessary for a soldier to be effective. Loss of these abilities is assumed to be incapacitating, the degree of which would depend on the assigned task.

5-4.2. (S) Probability of Kill or Incapacitation

(U) An old criterion of wounding power is the 58 foot-pound rule, which states in its crudest form that missiles with 58 foot-pounds of kinetic energy or less do not kill, and that those with more than 58 foot-pounds do kill. Although it is roughly applicable to unstabilized fragments of particular weights, the 58 foot-pound rule is particularly inapplicable to the evaluation of modern kill mechanisms.

(U) Indeed, reflection about even a few common wounding situations indicates that no single, simple, energy criterion is suitable for general application. For example, a two-hundred pound football player, falling three feet upon a tough opponent, and hitting him with 600 foot-pounds of kinetic energy, frequently causes no injury or incapacitation at all. On the other hand, a woman by pushing a dagger with a force of approximately 12 pounds for a distance of six inches into a man's chest, can kill the man by an expenditure of only about six foot-pounds of energy.

(S) In 1956, F. Allen and J. Sperrazza proposed a new formula which takes into account the target soldier's duties, and the span of time from wounding to incapacitation (Ref. 1). In this concept, a soldier is considered a casualty when he is incapable of performing his assigned tasks because of the effect of the wound. Older methods of analysis neglected these finer points and considered the soldier incapacitated only if fatally or severely wounded. The new formula (Ref. 1) proposed by Allen and Sperrazza is:

$$P_{hk} = 1 - e^{-a(mV^{\beta} - b)^{n}} \qquad (5\text{–}1)$$

In the formula, P_{hk} is the conditional probability that a random hit by a steel projectile will incapacitate soldiers in specific tactical roles (military stress situations; i.e., defense, assault, etc.). Also, in the formula, m is the fragment weight in grains, V is the striking velocity, in ft/sec., and a, b, n, and β are parameters whose values are derived from an analysis of the experimental data, based on several military stress situations, and on several discrete times-to-incapacitation after wounding.

(S) An analysis of the experimental work performed revealed that a value of $\beta = 3/2$ best fits the data. Values of the other parameters were determined for 14 combinations of military stress situations and times-to-incapacitation after wounding.

(S) Plots of P_{hk} vs $mV^{3/2}$ for all of the cases considered showed many similarities. Also, it was noticed that on the average four of the curves seemed to represent a majority

TABLE 5–1 (S). STANDARD PERSONNEL—INCAPACITATION TEST CASES (U)

Standard Case No.	Stress Situation	Cases Represented
1	Defense 1/2 min.	Defense 1/2 min.
2	Assault 1/2 min.	Assault 1/2 min. Defense 5 min.
3	Assault 5 min.	Assault 5 min. Defense 30 min. Defense 1/2 day
4	Supply 1/2 day	Supply 1/2 day Supply 1 day Supply 5 days Reserve 1/2 day Reserve 1 day

of the fourteen curves. The four cases chosen as standard, and the types of cases for which they are representative, are given in Table 5–1. Four different military stress situations are involved. The time following each case is the maximum time allowed for considering the soldier to be incapacitated in his function or duty.

(S) Tables of the parameters of P_{hk} vs $mV^{3/2}$, and plots of the curves, for Cases 1 through 4 are given in Tables 5–2 and 5–3, and Figs. 5–1 through 5–4, respectively. It is noted that the described criteria provide a major advance over the crude rules formerly used. However, they are based on experimental data limited to the use of steel fragments, only four fragment weights, and a limited number of impact velocities (3 per fragment). It is to be expected that refinements and revisions to the current criteria will be made as more data and new techniques are introduced.

(S) An illustration of an additional experimental study of incapacitation by projectiles is given in Table 5–4. This case is concerned with the conditional probability that a random hit by a caliber .30 rifle bullet (M2) will incapacitate within 300 yards (Ref. 3). Such work on bullets is still underway. Consequently, the values listed in the table are subject to revision.

(S) Work has also been accomplished on estimating the probability of incapacitation of

TABLE 5–2 (S). VALUES OF *a*, *b*, AND *n* FOR UNSTABILIZED FRAGMENTS

(P_{hk} vs $mV^{3/2}$) (Ref. 2) (U)

Case No.	*a*	*b*	*n*
1	0.88771×10^{-3}	31,400	0.45106
2	0.76442×10^{-3}	31,000	0.49570
3	1.0454×10^{-3}	31,000	0.48781
4	2.1973×10^{-3}	29,000	0.44350

TABLE 5–3 (S). VALUES OF *a*, *b*, AND *n* FOR NON-TUMBLING FLECHETTES

(P_{hk} vs $mV^{3/2}$) (Ref. 2) (U)

Case No.	*a*	*b*	*n*
1	0.55311×10^{-3}	15,000	0.44371
2	0.46134×10^{-3}	15,000	0.48535
3	0.69193×10^{-3}	15,000	0.47352
4	1.8579×10^{-3}	15,000	0.41498

TABLE 5–4 (S). PROBABILITY VALUES OF INCAPACITATION BY A RANDOM CALIBER .30 HIT (U)

Stress Situations of Target Troops	Time After Wounding		
	30 sec.	5 min.	30 min.
Assault	0.61	0.73	0.89
Defense	0.49	0.65	0.84
Reserve	0.64	0.74	0.90
Supply	0.79	0.86	0.93

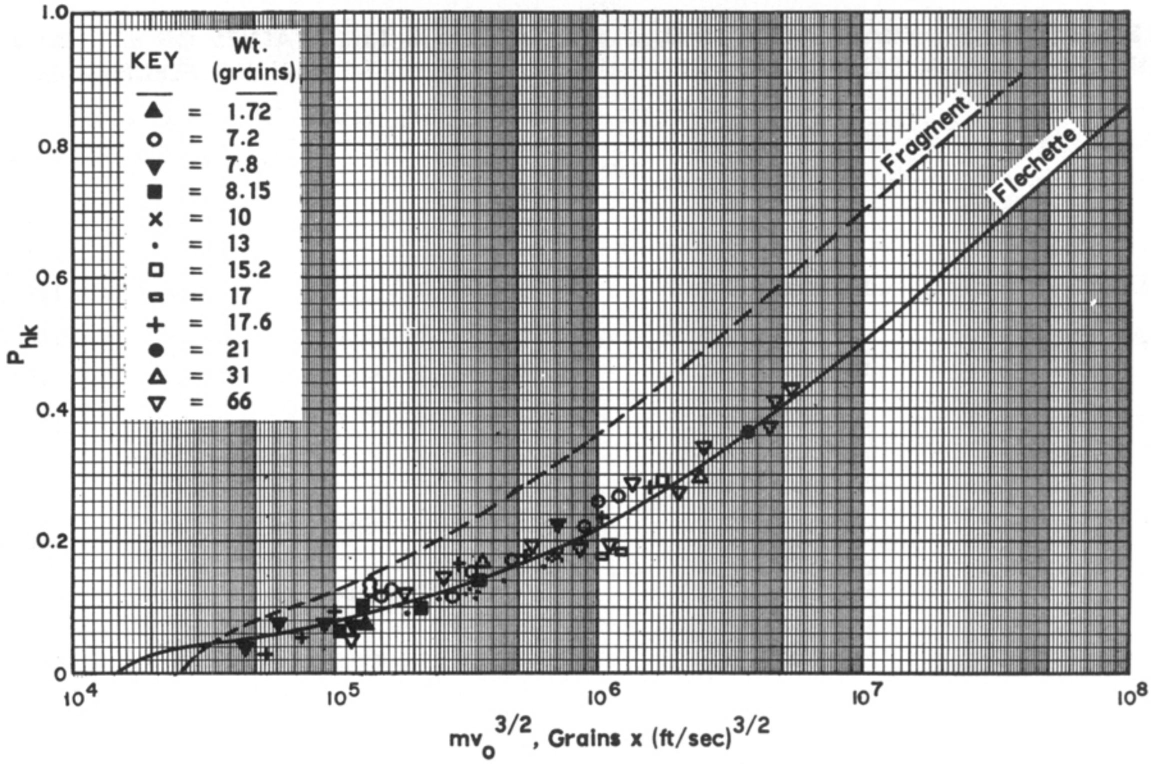

Figure 5–1 (S). Probability of Incapacitating a Soldier with an Unstabilized Fragment or a Non-Tumbing Flechette, Case 1, Defense 1/2 Minute (U)

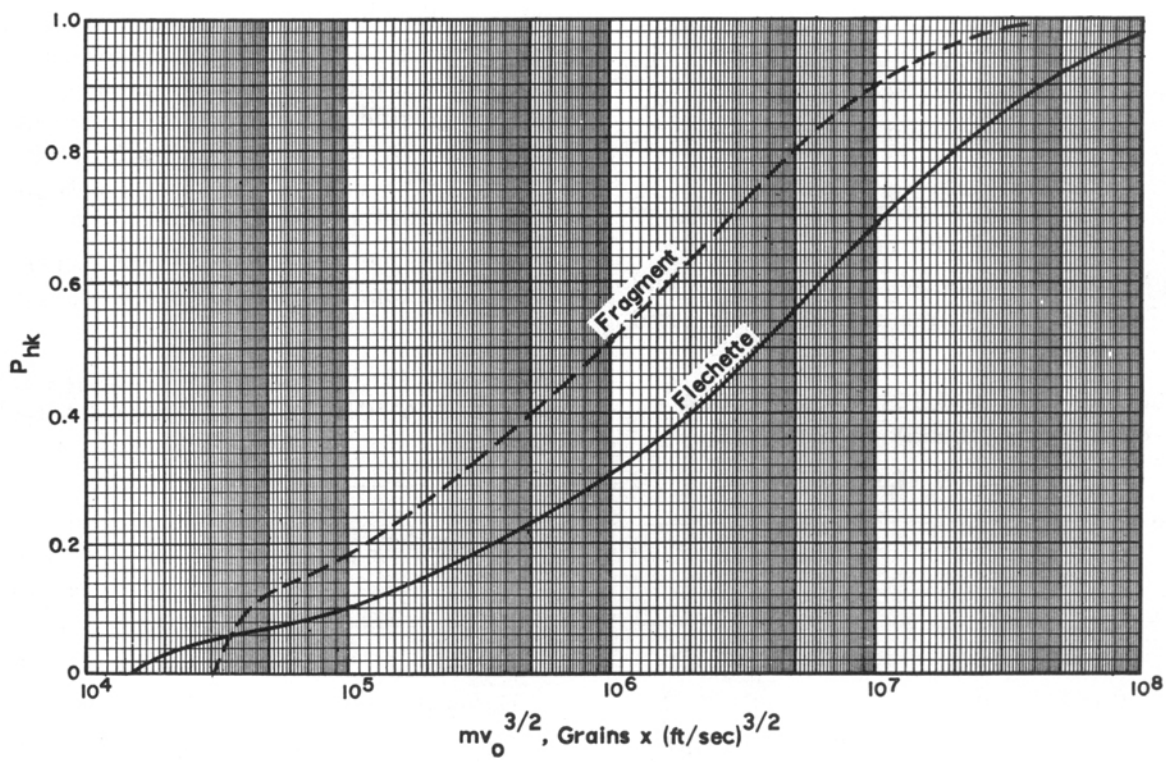

Figure 5–2 (S). Probability of Incapacitating a Soldier with an Unstabilized Fragment or a Non-Tumbling Flechette, Case 2, Assault 1/2 Minute (U)

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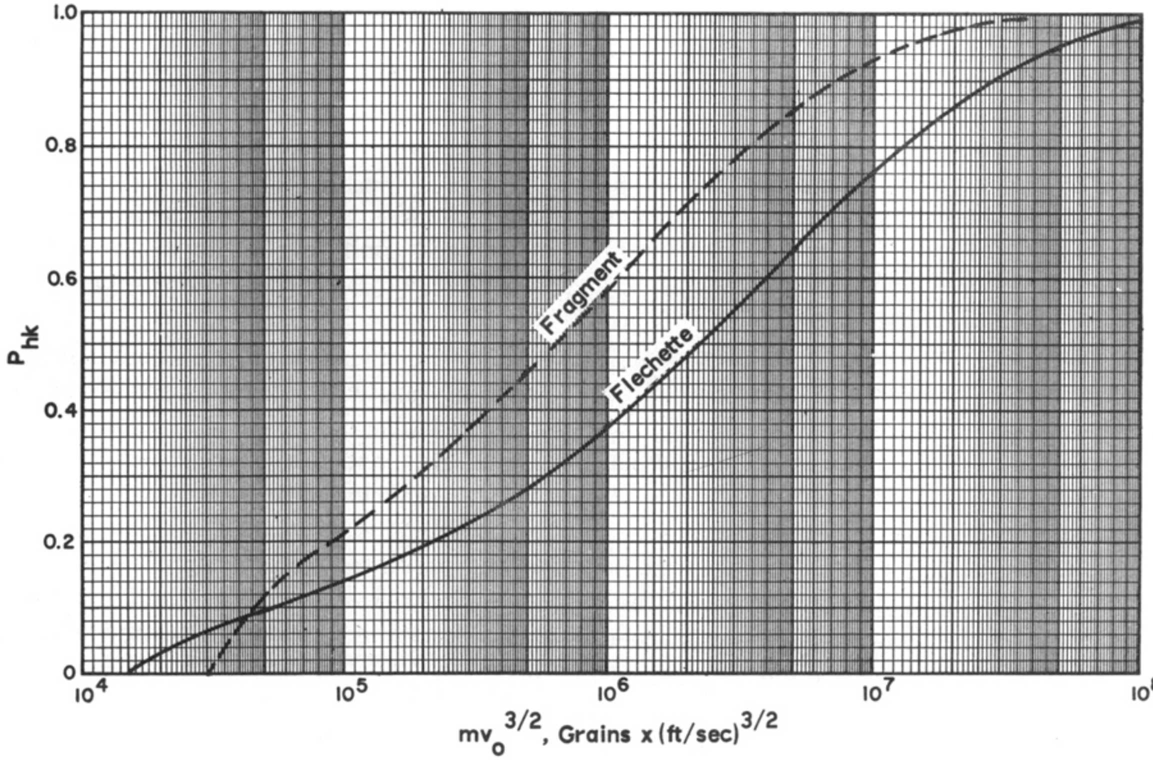


Figure 5–3 (S). Probability of Incapacitating a Soldier with an Unstabilized Fragment or a Non-Tumbling Flechette, Case 3, Assault 5 Minutes (U)

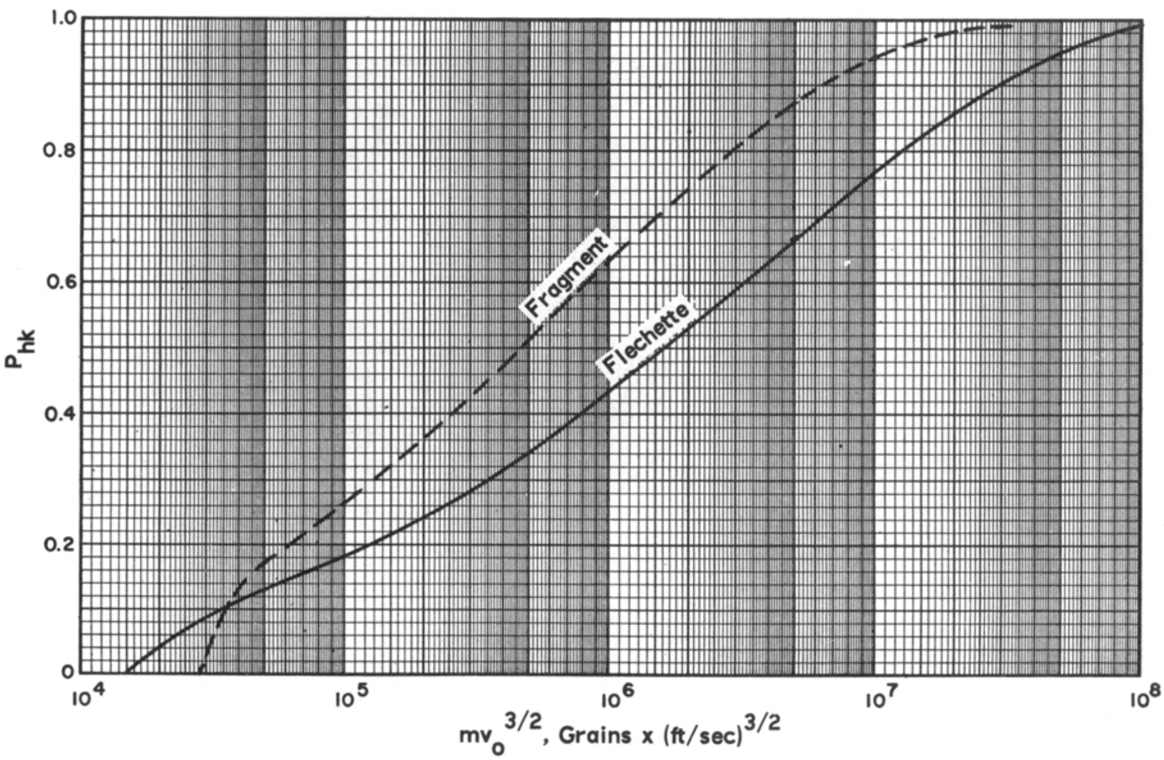


Figure 5–4 (S). Probability of Incapacitating a Soldier with an Unstabilized Fragment or a Non-Tumbling Flechette, Case 4, Supply 1/2 Day (U)

Chapter 6 (S)

GROUND VEHICLES

Section I (U)—Introduction

6–1. SCOPE OF THE CHAPTER

This chapter describes methods of collection of terminal ballistic data related to the incapacitation or defeat of ground vehicles. The purpose of this chapter is to describe how experimental tests are conducted which will determine the interaction between kill mechanism and target. The target upon which final terminal ballistic data is desired is the actual vehicle itself. However, because of the fact that all tests are limited in the amount and accuracy of the data that they will provide, it has been found necessary to conduct many kinds of tests in order to obtain the desired information.

Many of the tests conducted are projectile or armor development tests. It does not require an extensive knowledge of terminal ballistics to realize that it is not practical to experiment with new armor materials by building entire tanks out of the material, and then shoot antitank projectiles at the tanks. Not only is this not economical, but it is impossible to obtain accurate measurements of the parameters involved. The series of tests described herein, from scale-model tests, to full-scale tests with simulated ammunition or targets, and to proving ground tests where real ammunition is fired at actual vehicles, are designed to provide accurate data which will permit a determination of the amount of damage done to a vehicle by a given projectile, given a hit on the vehicle.

Although many different tests are described in this chapter, and a considerably large body of data is thereby provided, such data is provided only to illustrate the kind of information which is gleaned from these tests. It is not the purpose, here, to provide a complete set of specific terminal ballistic data. Similarly, the tests described are not considered to be conclusive, and are chosen to illustrate the manner in which a test is set up, conducted, and analyzed in order to provide useful information.

The techniques of gathering and analyzing terminal ballistic data are constantly being studied and improved by the experts engaged in this work. Every effort was made to report the latest experimental techniques in this section. For this reason, some of the references cited may describe a procedure slightly different from that reported herein.

The words "lethality," "effectiveness," "kill," and "vulnerability" are used frequently in this chapter. In order to be sure that the connotation of these words is understood, as used herein, they are briefly defined.

"Lethality," and "warhead effectiveness" are used synomymously, to refer to the damage producing capabilities of achieving a particular kill effectiveness against a ground vehicle target. "Kill" is sometimes used synomymously with "damage." Although the words "kill" and "lethal" have an all-or-nothing meaning in common usage, they have here an implication that the terminal effects may result in something less than total destruction.

"Vulnerability" refers to the susceptability of a vehicle to damage or destruction by a kill mechanism or particular projectile. The vulnerability of a vehicle to a given type of attack will vary over its surface, for a given attack direction, as well as with attack direction. Consequently, a vehicle cannot be said to be "vulnerable" or "invulnerable" to a given type of attack, but it can be rated on the basis of probability of being incapacitated by a conventional type of attack.

6–2. CROSS-REFERENCE INFORMATION

Ch. 3, Sec. II describes the ground vehicle as a target, as well as the ways in which it can

be killed, incapicitated, or rendered incapable of performing its functions. The various kill mechanisms of significance in this respect are discussed in the various sections of Ch. 2. Of additional interest, because people are affected when ground vehicles are under attack, is Sec. I of Ch. 3, Personnel. Finally, the collection and analysis of data concerning the various, pertinent mechanisms, as such, is covered in Ch. 4. All of this applicable material should be examined before proceeding with the present chapter. Where necessary, reference is made in the present chapter to particular portions of this material.

Section II (C)—Test Parameters

6-3. (U) INTRODUCTION

A terminal ballistic test of a projectile against armor may ordinarily be considered to have one of two purposes: to obtain penetration data, or to obtain vehicle damage data. Penetration data is desired so that the interaction of the projectile-armor combination may be understood. Test parameters must be selected so that the effect of varying projectile characteristics against constant armor characteristics may be determined, and so that the effect of varying armor materials and properties against specific projectiles can be determined. Damage data is desired to obtain some measure of what actually happens to a vehicle when it is hit by a projectile. A hit on the vehicle with a powerful projectile may not result in a complete penetration (i.e., a perforation), and even a perforation of the vehicle's surface does not guarantee that the vehicle will be disabled. A test which is intended to provide damage data must determine the vulnerability of the vehicle from many angles of attack, and with respect to one or more projectiles of known capabilities. The test must be arranged so that the effect of the various projectile—vehicle parameters upon the vulnerability of the vehicle may be determined.

6-4. (U) DESIGN OF THE EXPERIMENT

Each experiment must be carefully designed to ensure that it provides realistic data.* The armor characteristics, and the projectile types and calibers, must be within the range of those suitable for an actual design application. The conditions of the experiment must be in accordance with the conclusions to be drawn. A test in which antitank ammunition is fired at a real tank is not a very good way of determining the resistance of steel armor to perforation, because it is too difficult to obtain exact measurements of those parameters which affect the resistance to perforation. Such a test is, however, suitable for obtaining damage data which describes the terminal effects of the projectile upon the vehicle. On the other hand, a simulated target (a piece of armor or target material) is suitable for use in obtaining penetration data.

It is necessary to delineate what constitutes success for these tests. For example, if a projectile penetrates just far enough into a piece of armor for a small piece of the armor to fly off the rear face, has the armor been defeated, or has the projectile been defeated? What is required in this case is a definition of complete penetration.

It is even more difficult to determine what constitutes success when assessing damage data respecting a vehicle. A vehicle is seldom destroyed by a projectile that strikes it. An impacting projectile may wound several personnel, or may damage or even destroy several components, when it strikes and perforates, and still not completely disable the vehicle. For these reasons, damage effects may be expressed as: some level of functional impairment (50% loss of mobility, 100% loss of firepower, etc.); vehicle-stoppage time limits (2 minutes, 5 minutes, 20 minutes, etc.); and vehicle-repair time limits (1 hour, 2 hours, 20 hours, etc., or beyond economical repair).

Component design data are desired with respect to both projectile and armor. When con-

*For more detailed information concerning experimental data, consult Ordnance Engineering Design Handbooks on *Experimental Statistics*, published in 5 Sections as ORDP 20-110 through -114.

ducting design development tests, as for example on a new armor material, a high ballistic limit indicates good armor performance and/or poor projectile performance. (The ballistic limit is the striking velocity at which a given type of projectile will perforate a given thickness and type of armor plate, at a specified obliquity. Refer to Par. 6–13.2.) The parameters of the test must permit evaluation of those properties and charteristics of the armor which will obtain the highest ballistic limit (always with respect to a specific projectile). An increase in the ballistic limit of the armor will, by definition, improve its resistance to penetration. On the other hand, projectile design tests are oriented toward obtaining the lowest ballistic limit that will permit complete penetration and thereby reduce the amount of energy required for perforation.

Although the above comments are directed toward ballistic limits of armor-piercing projectiles and shell fragments, comparable information with respect to concussion (offensive) grenades, mines, or high-explosive shells would provide the amount of explosive needed for these weapons, to defeat certain types of armor at given standoff distances. With other types of projectiles, also, the purpose of the tests is to determine some quantitative measure of the amount of energy needed to defeat some specific target material.

6–5. (C) PROJECTILES, TYPES AND PROPERTIES

6–5.1. (U) General

A large number of projectiles have been developed for use against ground vehicles, both armored and unarmored. In general, these projectiles may be categorized according to the manner in which perforation or destruction is obtained (kinetic-energy projectiles, high-explosive blast shells, etc.), or in terms of specific design application (armor-piercing, armor-piercing capped, grenades, mines, etc.). In this publication, the treatment of high-explosive rounds is generally more comprehensive than the treatment given kinetic-energy rounds, because with respect to ground vehicles, most of the testing has been with armor piercing rounds.

6–5.2. (C) Armor-Piercing

6–5.2.1. (U) *Introduction*

The projectile most commonly associated with defeat of ground vehicles is the armor-piercing (AP) type. Evaluation of the armor-piercing projectile, and improvements in armor materials, have resulted in the development of several different models. The simplest AP round incorporates the armor-piercing shot (or monobloc) projectile. All the other projectiles shown are variations of the basic AP shot, and are designed to compensate for its limitations.

6–5.2.2. (C) *Armor-Piercing Shot*

The armor-piercing shot (or monobloc) projectile is solid ammunition, without explosive charge or fuze, and with or without a false ogive or windshield (ballistic cap). Such ammunition is made of specially heat-treated alloy steel, usually of the molybdenum-chromium or manganese-molybdenum variety. It is decrementally hardened to provide a very hard nose, in order to stress the armor plate at impact (and to retain its own shape). The body is not quite as hard as the nose, so that the body can pass through the plate without breaking up. Since World War II, conventional armor-piercing shot developed for attack of tank armor have generally been as hard as reasonably possible (60 to 64 R_c at the nose). Shot of high hardness is more resistant to deformation and shatter than soft shot, and is better at low and intermediate obliquities for the defeat of overmatching armor plate. The ideal projectile would have high density, maximum hardness, and maximum bending and compressive strength. Because these qualities are often mutually exclusive, the various projectile materials represent attempts to attain an optimum compromise. Some of the more common alloys that have been found suitable for use as AP shot are listed in Table 6–1 (Ref. 1).

The hardness pattern for shot made as above will vary from 60 to 64 R_c at the nose to 40 to 45 R_c at the base. Typical geometry of the projectile provides an approximately 1.2- to

TABLE 6–1 (C). COMPOSITION OF SELECTED AP ALLOYS (U)

Type of Steel Alloy	Per Cent by Weight							
	C	Mn	Si	Ni	Cr	Mo	V	B
NE 98V65	0.63 avg.	0.99	0.32	0.99	0.93	0.32	0.08	.....
NE 86V65	0.61 avg.	0.96	0.30	0.57	1.18	0.14	0.08	.....
41 B 60	0.65 max.	1.01	0.43	....	0.90	0.18	....	0.005
FS 4160	0.62 max.	0.99	0.29	....	1.08	0.21	....	.....
SAE 4150	0.55 max.	1.02	0.32	0.36	1.04	0.23	....	.....

1.4-caliber-radius ogival-nose configuration. As with many other high-velocity rounds, the shot frequently has no boat tail, primarily because it is not effective at velocities much above the speed of sound. Over-all length of the monobloc projectile would not be much more than 3 calibers. For additional details pertaining to steel projectile design, see Ref. 2.

The windshield of the projectile is contoured to obtain the best exterior ballistic characteristics. It is made either of thin-gauge sheet metal or, often, of a die-cast aluminum alloy. Welding, crimping, and epoxy-resin bonding materials have all been used to fasten the windshield to the projectile.

Because the ultimate goal of the projectile is destruction of the target, it must, by virtue of its striking energy, establish the maximum possible stress in the armor plate. To accomplish this vital condition, it must present a minimum area to the plate during the entire period covering its contact with the plate. This is possible only if the projectile is of such strength as to resist shattering. It follows, therefore, that resistance to shattering is one of the most important characteristics which an AP shot must possess.

The function of armor plate is to defeat by shattering or otherwise stopping the AP shot by a combination of plate hardness and obliquity. The forces acting on a projectile at impact (Fig. 6–1) may be idealized as follows:

1. An axial force, shown in view (A), which creates compressive stresses or waves, the amplitude of which may be of such magnitude as to cause fracture.
2. A transverse bending force, which may be induced by the yaw of the projectile at the time of impact, shown in view (B), or by the effect of oblique plugging penetration tending to right the projectile, shown in view (C). The bending moment so induced gives rise to a shearing stress, in both cases, normal to the axis of the projectile.

6–5.2.3 (C) *Armor-Piercing-Capped (APC) Shot*

The problem of shatter has been ameliorated by the use of armor-piercing caps. The armor-piercing-capped (APC) projectile may be solid, or may have a small explosive filler. The cavity for this explosive charge cannot be large. It must be in the base of the projectile, otherwise the nose would not be sufficiently strong to penetrate armor. The charge seldom exceeds 5 per cent of the total projectile weight. The projectile is provided with a base-detonating (BD) fuze.

The armor-piercing cap is, as the name implies, a cap fitted over the nose of the projectile. It is made of alloy steel, differentially hardened from striking face to base. The precise nature of the cap action is not completely understood, but general agreement is found on certain basic points. Differential heat treatment permits the cap to present a hard surface to initial impact, setting up a tremendous stress in the target plate. The tough interior of the cap aids in absorbing the impact shock on the projectile. That the cap itself is shattered in the process is of secondary interest, although it may bring

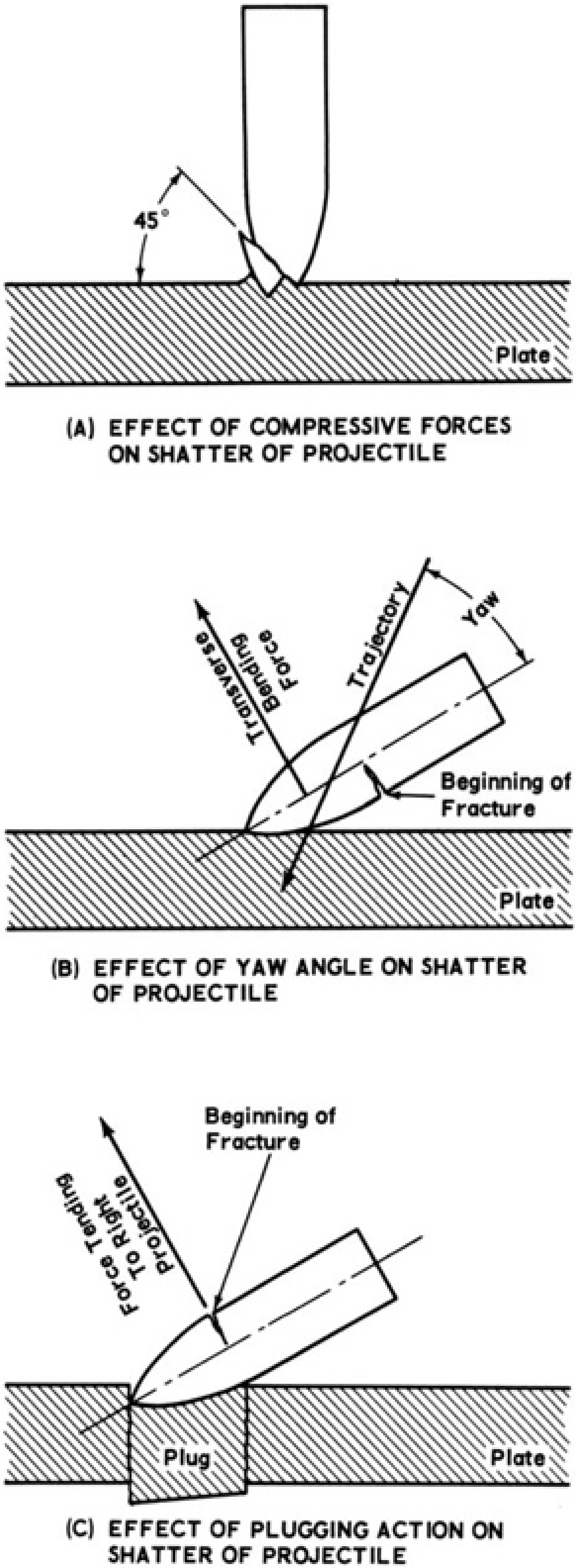


Figure 6–1. Effect of Impact on AP Shot

about slightly lowered projectile performance against homogenous plate. The cap also provides a relatively favorable stress distribution over the nose of the body of the projectile, which lessens the body's tendency to shatter.

As indicated, the purpose of the AP cap is to prevent shatter of the projectile. In cases where the monobloc would not shatter, the use of a cap is a detriment. On the other hand, if shatter of the monobloc is likely to occur, then the cap, by keeping the main body of the projectile intact, will decrease the limit energy required for perforation by the projectile as a whole, despite some loss in perforating ability due to the disintegration of the cap. Thus, the limit energy may be either increased or decreased by the attachment of a cap, and unless the conditions of impact are specified, no answer can be given to the question of whether a capped or a monobloc projectile perforates a greater thickness of armor.

The shatter of a shot usually begins with collapse of the nose and the breaking up of the shot into small pieces. If the shot shatters when the penetration is almost complete, the fragments may break through and complete the perforation. This is counted as a success, because the shower of fragments may be more damaging than a single shot. If the shot can be so designed that the nose will hold together when the body shatters, the chances of successful perforation are greatly improved.

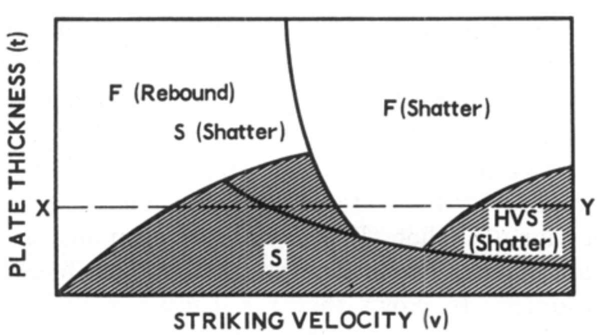
The behavior of a given type of shot can be usefully represented by a phase diagram which relates the success or failure of the shot, at a constant angle of attack, with the variables of striking velocity and plate thickness. Fig. 6–2 shows a hypothetical phase diagram, which may be used to illustrate the possible modes of behavior of a shot. It is used merely for illustration; many variations of it are possible in practice. It shows that for a given thickness, marked by the line XY, that as the velocity is increased, it is possible to pass successively through phases of: (1) failure due to low velocity; (2) success with the projectile remaining intact; (3) success with shatter; (4) failure with shadow; (5) high velocity success with shatter. It may be seen that increase of

striking velocity does not necessarily increase the chance of success, and that optimum values of striking velocity may exist.

Recent findings based upon scale-model firing tests (Ref. 3) show that capped projectiles surpass monobloc projectiles for attack of heavy homogenous armor, in the obliquity range of 20 degrees to 40 degrees, and at volocities above 1,700 ft/sec. In the higher range of 45 degrees and up, monobloc projectiles perforate a greater thickness of armor at velocities below 4,200 ft/sec. The apparent superiority of monobloc projectiles at greater obliquities results from the tendency of the monobloc nose to shatter, causing the remainder of the projectile to tip to an angle more nearly normal to the plane of the plate. Perforation is achieved by punching action, in spite of partial shatter of the projectile. In this obliquity range, the capped projectile has a strong tendency to ricochet.

6–5.2.4. (C) *High-Velocity Armor-Piercing (HVAP) Shot*

(C) HVAP shot has been described in the past as hyper-velocity armor-piercing shot, rather than high velocity. However, as currently used, the term hyper-velocity impact is associated with impact velocities where the behavior of target material and projectile are quite different than is encountered with projectiles from conventional guns (Ref. 4). For



Symbols:
F = Failure
S = Success
HVS = High Velocity Success

Figure 6–2 (C). Phase Diagram for Representative AP Shot (U)

this reason, HVAP shot is referred to herein as high-velocity, armor-piercing shot.

(C) Basically, HVAP shot consists of a very hard, high-density core surrounded by a jacket (carrier) of lighter metal. The core is the penetrating component of the complete projectile. For a given gun-bore diameter, this type of projectile is much lighter than ordinary armor-piercing shot. Consequently, the HVAP shot can be accelerated to a much higher muzzle velocity, which will increase its striking energy. Further, because the penetrating core is made of a high-density material (usually tungsten carbide), greater kinetic energy per unit area is available, at any given striking velocity, than is available with a steel projectile.

(C) The base of the carrier (jacket) is usually made of steel, because of the stresses imposed on it when the projectile is fired. Furthermore, the rotating band is frequently an integral part of the steel base, unlike on lower velocity projectiles, which can make use of softer metal bands under lower bearing pressures. The decrease in over-all weight, while helping to give greater muzzle velocity, also results in a lower (hence undesirable) inflight ballistic coefficient (C) than is found in the discarding sabot type of round (Par. 6–5.2.5, following).

(U) The ballistic coefficient is one of the most important parameters which appear in the formal differential equation of a trajectory. It is usually expressed in the form,

$$C = \frac{W}{i(D)^2} \tag{6–1}$$

where

W = the weight of the projectile, in pounds,

D = the diameter of the projectile, in inches,

and

i = an empirical factor, called the form factor, which compares the drag coefficient of the projectile under consideration, at a given velocity, with that of an arbitrary standard at the same velocity.

(U) The ballistic coefficient (C) indicates the ability of a projectile to overcome air resistance; the larger the value of C, the less the retardation. Coefficient C is commonly thought of as a constant for a given projectile, and is given as proportional to the sectional density of the projectile ($\frac{W}{D^2}$ ratio) and its aerodynamic efficiency. At relatively low initial velocities, such as those given by the lower zone charges of field howitzers, the loss of velocity due to air resistance is relatively small as compared with that which is produced when the initial velocities are relatively high. Also, the effect of the ballistic coefficient increases as the initial velocity increases. It is evident that projectiles that are to be fired with high initial velocities should be made as dense as other conditions will permit, and should be given a shape which is aerodynamically as efficient as possible.

(C) A typical core material for HVAP shot is a sintered tungsten-carbide (wc) with the properties shown in Table 6–2 (Ref. 5).

(C) The geometry of a typical tungsten-carbide core is similar to that of the monobloc round. One is shown in view (A), as projectile H–13, in Fig. 6–3. Also shown on the same figure are experimental, compound-conical, tungsten-carbide core designs. Tungsten-carbide cores have a density about 1.7 times that of steel. They are heat-treatable to about 69 to 72 points (Rockwell "C"), rather than to the 60 to 64 points of typical steel AP projectiles.

(C) HVAP projectiles are fired at high muzzle velocities, above 3,500 ft/sec., and usually in the neighborhood of 4,000 ft/sec. They have excellent armor-piercing abilities if used at normal battle ranges; however, their armor-piercing abilities fall off rapidly at longer ranges, due to the low ballistic coefficient.

(C) Because the jacket of this type of projectile is rigidly attached to the core (which has a diameter about half that of the gun bore) and does not fall off until in contact with the target, the HVAP projectile is also known as the composite rigid, or compo-rigid, type.

6–5.2.5 (C) *High-Velocity Armor-Piercing Discarding Sabot (HVAP-DS) Shot*

The discarding sabot type of HVAP shot (Fig. 6–4) uses a jacket (also known as carrier or sabot) that falls away from a sub-projectile (subcaliber projectile) after the composite projectile leaves the muzzle, allowing the sub-projectile to proceed toward the target. The over-all weight of the composite missile is much less than that of a monobloc projectile of the same caliber for these reasons: the diameter of the core is approximately half that of the complete projectile; as much of the carrier as is possible is made of a light metal, such as aluminum; and the body is recessed, where possible. Consequently, the muzzle velocity of the sub-projectile will be greater than that of a monobloc projectile whose caliber equals that of the initial composite projectile. In addition, the smaller sub-projectile presents less air resistance. Therefore, its ballistic coefficient, C, will be high, and it will have a low rate of loss of muzzle energy, arriving at the target with a higher striking energy. As a net effect, the sub-projectile is effective over a much longer range than the composite rigid type (HVAP shot) of projectile.

The sub-projectile carrier is designed to present a large cross-sectional area to the pressure

TABLE 6–2 (C). PROPERTIES OF A TYPICAL SINTERED, TUNGSTEN-CARBIDE CORE (U)

Composition				Hardness Rockwell "A"	Hardness Rockwell "C"	Density (gm/cu cm)
% Tungston Carbide	% Cobalt (Binder)	% Free Carbon	% Iron			
84 to 90	16 to 9	0.3 max	0.7 max	86 to 88	69 to 72	13.9 to 14.5

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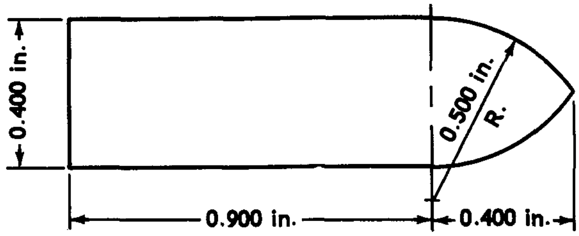
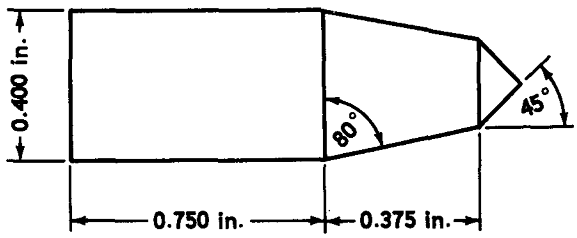
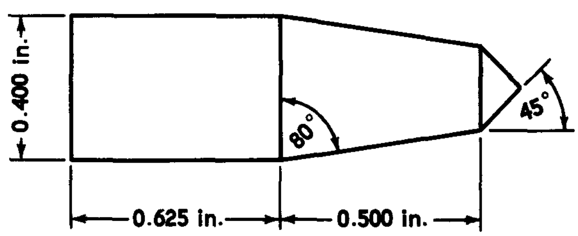


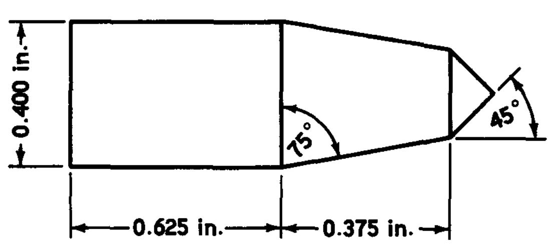
(A) PROJECTILE H-13
WEIGHT 33.0 GM.



(B) PROJECTILE H-19
WEIGHT 30.1 GM.



(C) PROJECTILE H-19C
WEIGHT 28.0 GM.



(D) PROJECTILE H-19D
WEIGHT 28.7 GM.

Figure 6–3 (C). Geometry of Typical (H–13) and Experimental Tungsten-Carbide Cores (U)

of the propellant gases, so as to impart velocity and spin to the sub-projectile. This carrier (or sabot) is discarded as it leaves the gun, thus allowing the subprojectile to continue toward the target unimpeded by the weight and air-resistance of the sabot. The sabot, usually made of aluminum, magnesium-zirconium alloy, or plastic, with or without a steel base, may be released (unlocked) from the sub-projectile by a device actuated by setback, propellant-gas pressure, or centrifugal force. The actual separation of the sabot from the sub-projectile is accomplished mainly by centrifugal force, air resistance, or both. The sabot, because of its poor ballistic shape and its low mass loses velocity rapidly, and the sub-projectile is set free soon after it leaves the gun.

One disadvantage of the sabot type of projectile is the danger that discarded pieces of jacket may strike friendly troops. From a safety viewpoint, it is necessary that the lethality of the sabot or its fragments be minimized. This is done in two ways: by assuring that the sabot will break up into many, small, low-energy fragments, which rapidly lose velocity; or by use of a design that minimizes the number of secondary fragments detaching themselves from the sabot.

Another important shortcoming of the HVAP-DS round is that the sabot is not always uniformly discarded at the muzzle, resulting in deflection of the projectile from its flight path. Further development work is being conducted on this problem.

6–5.2.6. (U) Summary of Armor-Piercing Projectile Parameters

The penetrating capabilities of HVAP shot are illustrated in the ballistic limit chart given in Fig. 6–68 in Par. 6–13.2. Significant parameters affecting armor-piercing projectile characteristics are summarized as follows:

1. For a given monobloc shot, or subcaliber projectile, varying metallurgical properties will affect the energy required for penetration. High hardness and density, with maximum bending and compressive strength, are desirable.

Chapter 7 (S)

GROUND STRUCTURAL TARGETS

Section I (U)—Introduction

7–1. SCOPE OF THE CHAPTER

7–1.1. General Content and Coverage

This chapter discusses the collection and analysis of terminal ballistic data with regard to ground structural targets of the following types: residential and commercial buildings; industrial and military complexes, such as oil refineries and missile bases; damage resistant structures, such as magazines and bomb shelters; and underground structures, such as tunnels and "hard sites." The effects of various lethal mechanisms on these types of targets is of interest to many different groups and individuals, each of whom will have somewhat different viewpoints. These viewpoints are illustrated in Table 7–1.

The terminal ballistician concerned with ground structural targets must provide qualitative and quantitative data in a form useful to each of the interested groups. Because of the different viewpoints represented, both the types of data and the manner of presentation in the chapter vary. In Sections II through V, the basic analytical and experimental techniques used in obtaining the data are discussed and

TABLE 7–1. TYPES OF TERMINAL BALLISTIC INFORMATION REQUIRED

Interested Group	Viewpoint	Examples of Type of Information Required
Corps of Engineers	Design and construction of damage resistant structures.	Weapon and structural parameters that influence target damage. Analytical techniques to relate these parameters to design practice.
Civil Defense Agency	Protection and evacuation of civilian population.	Gross weapon effects for education of civilian population.
Field Forces	Employment of weapons to accomplish stated missions in an effective and economical manner, and protection of personnel.	Target vulnerability data reduced to a simple form for employment in weapon selection formulas. Gross weapon effects for education of military personnel.
Weapon Designer	Conception and design of weapons with increased terminal effectiveness.	Weapon design parameters that influence the lethal mechanism. Knowledge of how the lethal mechanism influences the terminal effectiveness.
Weapons System Analyst	Analysis of systems, to determine the variation of terminal effectiveness with system parameters.	Knowledge of the influence of system delivery accuracy on the terminal effectiveness.

illustrated. Section VI illustrates some of the forms in which the data are presented to users.

7–1.2. Method of Handling the Problem

As discussed in Ch. 3, Sec. III, ground structures are vulnerable primarily to air blast and ground shock, and secondarily to fire and fragmentation. This chapter deals primarily with the effects of air blast and ground shock on surface and underground structures. (The terms "ground" and "surface" are used interchangeably throughout both of these discussions.) A flow chart defining this specific terminal ballistic problem is shown in Fig. 7–1.

The quantitative form of the lethal mechanism is determined by the weapon parameters and the environment of the particular tactical engagement considered. The lethal mechanism evidences itself at the ground target in the form of dynamic (time dependent) loading. The target responds to this loading, with the target geometrical and structural parameters determining the exact form of the dynamic response. Two significant points are illustrated in the flow chart. First, the loading is determined (in part) by the geometry of the target. In the case of blast loading, for example, both the diffractive and drag loadings are dependent upon the shape of the target. Second, the loading is affected by the response of the target. A building with windows, for example, will suffer an initial loading which will break the glass, and the pressures will then be redistributed, resulting in a different loading. As a result of the dynamic response, the target suffers certain damage which must be assessed in accordance with a predetermined damage criteria.

Generally speaking, this aspect of the problem is more qualitative than quantitative. For a given weapon, target, and engagement environment there are many uncertainties associated with both the loading and the response. The parameters associated with the lethal mechanism, the loading, the target response, and the weapon delivery are all subject to statistical variations.

The final step in the problem is to assign (by analysis) a probability to the damage assessment. In this chapter, information pertaining to all aspects of the problem, as described, is presented. The primary emphasis is on the experimental and analytical techniques used in determining target loading and response.

7–2. CROSS-REFERENCE INFORMATION

The general discussions of blast, ground shock, fragments, and fire, as kill mechanisms applicable to ground structural targets, are located in Ch. 2, Secs. IV, VI, I, and VII, respectively. Target vulnerability of ground structures is dealt with in Ch. 3, Sec. III. Finally, portions of Secs. I and II of Ch. 4 deal with the collection and analysis of data concerning the kill mechanisms of blast and fragmentation, respectively, in terms of ground structures. All of this material should be examined prior to the study of the present chapter. Cross-references are made, as necessary, to these various, related bodies of information.

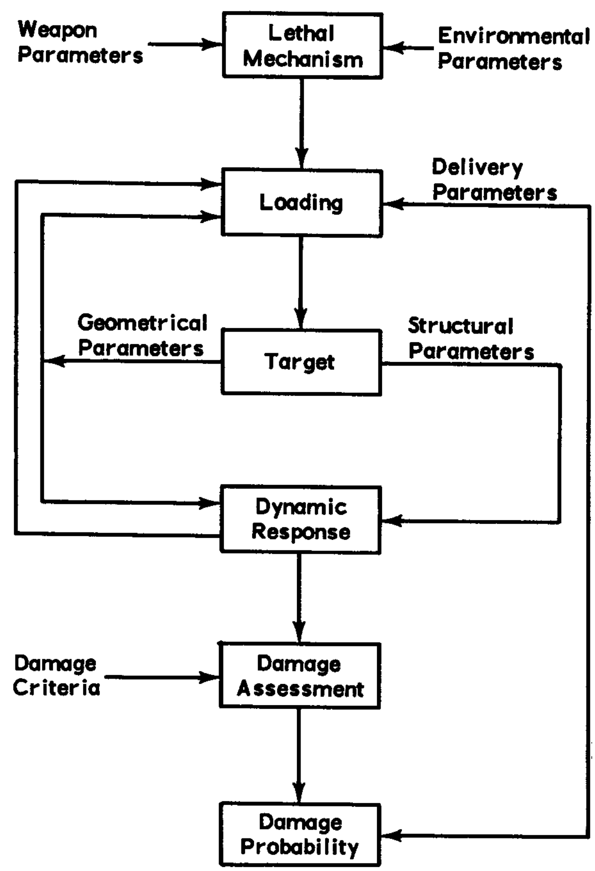


Figure 7–1. Flow Chart Representation of the Terminal Ballistics of Ground Targets

Section II (S)—Full-Scale Experiments

7–3. (U) INTRODUCTION

This section is devoted to a discussion of full-scale experimentation using both nuclear and conventional (HE) explosives. Nuclear test operations are quite complex and costly, and in reality consist of a large number of individual programs each designed to produce specialized information. For this reason, the information presented is quite general. A more detailed discussion of underground magazine safety tests, and a full-scale conventional test program are given, to indicate the methods of testing and the types of instrumentation which can be employed in the field.

7–4. (S) NUCLEAR WEAPONS EFFECTS TESTS

7–4.1. (U) General

The bulk of the available data on nuclear weapons has originated from surveys of the results of the atomic bomb explosions over Hiroshima and Nagasaki, or from extensive series of full-scale nuclear weapon detonations. The vast confusion surrounding the bombings at Hiroshima and Nagasaki severely limited the analytical quality of the damage survey. Consequently, the full-scale nuclear tests became a necessity, in order to accumulate sufficient information to enable the prediction of the effects of any future employment of nuclear weapons.

Beginning in 1946 with Operation Crossroads (Ref. 1) and ending in October 1958 with Operation Hardtack (Ref. 2), literally hundreds of tests were conducted. The bulk of the shots made over and under water, the extremely high altitude shots, and all of the high yield (megaton range) shots were conducted at the Eniwetok Proving Ground in the South Pacific. Experiments at the Nevada test site have been limited to explosions of lower yield, but have nevertheless provided information and data of primary importance.

The various operations have included bursts of every type; high altitude airbursts, low altitude airbursts, contact surface bursts, and subsurface bursts have been detonated in different environments. These experiments were conducted in both sea and land areas, and in combinations of the two under various meteorological conditions. The damage mechanisms accompanying a nuclear explosion (blast and thermal and nuclear radiation) have been studied in detail, as have the factors that influence the propagation of these phenomena (terrain, weather, altitude, etc.).

The large number of detonations have been studied in an attempt to correlate several important factors. In addition to obtaining information concerning the blast overpressure, dynamic pressure, thermal radiation, and nuclear radiation produced by an explosion of given yield at known altitude, it is necessary to coordinate this knowledge with the response of various types of targets to the different phenomena. The target response can then be related to damage. From this information, a criterion may be established which will allow the prediction of damage from any type and yield of detonation.

Normally, a nuclear test operation is planned to include many shots and to gather a wide variety of data. The details of the organization of such an extensive operation must necessarily be dependent upon a great many factors. Therefore it is not only impractical, but virtually impossible to establish a testing procedure which may be utilized in every instance. Each case must be examined separately. However, an example of the organization of past operations can prove useful in providing some insight into the problem. In the following paragraphs, the objectives, organization, operation and results of Operation Hardtack will be discussed in detail.

7–4.2. (S) Description of Operation Hardtack

Operation Hardtack was conducted in two phases, one at Eniwetok Proving Ground (EPG), the other at the Nevada Test Site (NTS). More than seventy nuclear devices were detonated during the two phases of the operation. Two series of tests were conducted to develop immediate tactical doctrines. Underwater shots were fired in two environments, one in relatively deep water, and one on the bottom of the Eniwetok Lagoon, at a depth of

about 150 feet. The objectives of the underwater shots were to obtain sufficient information to close the gaps left by previous underwater experiments, and to obtain information concerning the effects of weapon types presently stockpiled. The second series of shots, consisting of four shots ranging in yield from no nuclear yield to 20 kilotons, employed devices that were being developed at that time for use in tactical situations by front line troops. Until this series of tests, only theoretical data, based on extrapolation from higher yield weapons, was available for explosions under 20 kilotons (Ref. 2).

Three very high altitude shots, ranging from 85,000 to 250,000 feet, were fired during the operation. No previous shots had been fired at this altitude. The primary considerations were partition of energy, effects on long range communications, world-wide fallout, and the effects on ICBM's in the immediate area.

In addition to these series, extensive investigations were conducted in fields of aircraft response, blast and nuclear radiation detection, and effect on underground structures. In general, operation Hardtack was a successful operation. Most of the objectives, especially those concerning underground structures, aircraft, underwater bursts, low yield detonations, and high altitude effects were accomplished.

Generally, the magnitude of a nuclear test operation requires that the tasks be distributed among several projects. In the operation Hardtack experiments, several separate programs were established. Program one was designed to determine air blast, underground shock, and underwater shock parameters and effects. Program two objectives were to determine the gross radiological hazard from underwater bursts, collect neutron-energy-spectrum data, determine prompt-neutron measurements at high altitude, obtain radiation measurements in the nuclear cloud, and collect prompt-gamma measurements and fallout data close to ground zero.

Program three was designated to determine the effects of underwater bursts on surface and subsurface vessels, and to study several types of land structures under various loading conditions. Program four was designed to determine the extent of retinal damage caused by direct exposure to high-altitude, high-yield weapons, and to correlate these results with existing, theoretical calculations. This program also included an extensive investigation of the effects on animals located in field fortifications and armored vehicles near low yield bursts. Program five was designed to provide input data to determine safe aerial delivery tactics.

Program six was assigned diversified objectives, which can be placed conveniently in four categories. The first of these was the determination of the feasibility of using the electromagnetic pulse as a detector of future bursts, and the study of the nuclear cloud by radar. The second was the investigation of high altitude ionization effects on communications, missiles, and antimissile missiles. The third was the investigation of nuclear radiation effects on fuzes and their components. The fourth consisted of experiments on underwater shots, to determine the feasibility of using a nuclear explosion to clear naval minefields.

Program eight evaluated laboratory methods of determining the effects of thermal radiation from the low yield shots. Program nine was established to provide documentary and support photography for the other projects. In addition, program nine coordinated the activities of the delivery system agencies with the specific projects (Ref. 2).

7–4.3. (U) Basic Method of Testing Ground Structures

During the years between Operations Crossroads and Hardtack, practically every imaginable type of structure has been tested and evaluated. The responses of each structural target to the various nuclear phenomena have been determined, and these data have been related to damage. Representative examples of this information are presented in Par. 7–22.3, following.

In general, a structural target of specific type is examined as follows. From previous nuclear tests, a prediction of the range and height of burst for a weapon of given yield, at which a desired level of damage will occur, may be made. Several targets are then set up, at vary-

ing distances from ground zero, where severe, moderate, and light damage (Ch. 3, Sec. III, Par. 3–12) are expected to result. These targets are oriented at different attitudes with respect to the center of the explosion. At each damage range, the targets then provide a study of various phenomena (face-on pressure, side-on pressure, etc.). The structures are instrumented to record information regarding the variation in magnitude and duration of the blast loading, the deflection and elasticity of the structure, the temperature, and the nuclear radiation dosage inside the structure. It should be noted that, dependent on the individual test, instrumentation for all of these phenomena may or may not be utilized at any one time. Other instrumentation is set up to provide free-field quantitative measurements of the blast, and of the thermal and nuclear phenomena.

After detonation, the free-field instruments provide data concerning the basic parameters to which the target is exposed. The response-instrument readings are correlated with the degree of damage, and the necessary adjustments to the data for the predicted ranges and height of burst, if any, are made.

The knowledge gained from full-scale tests, with regard to target loading and response and to the basic parameters governing this response, are required to establish design and damage criteria and to permit the verification of laboratory and theoretical studies (Ref. 3). The results of these tests are invaluable both to the planning of nuclear offensive action and to the establishment of adequate defensive measures.

7–5. (S) REPRESENTATIVE UNDERGROUND-MAGAZINE SAFETY TEST

7–5.1. (S) General

Underground magazines have been used for many years for the storage of high explosives. The safety problems associated with such magazines become particularly acute when it is necessary to place the magazines in inhabited areas. A full-scale experimental study has been made of the hazard from accidental detonation of NIKE-HERCULES missiles in their underground magazines. This study is reported in Ref. 4, and is discussed here in detail as representative of the experimental techniques which have been used to determine the safety of underground magazines.

7–5.2. (S) Purpose and Organization of the Test

Department of the Army criteria for siting NIKE-HERCULES installations permit construction of the underground storage magazines at 528 feet from the nearest inhabited building, or one-fourth the distance which is permitted for explosives stored in unbarricaded magazines above ground. To validate the present explosive "quantity-distance" safety criteria, the Ballistic Research Laboratories were requested, through the Safety Branch, Office of the Chief of Ordnance, to perform from one to three full-scale tests. These were to simulate an accidental warhead detonation within a magazine containing a normal complement of six NIKE-HERCULES missiles. The missiles were to be complete except for their guidance systems, and were to contain the T–45 fragmentation-blast type warhead.

Evaluation was to be made of the effects of the "accident" on the storage magazine, on the underground personnel shelter adjacent to the storage magazine, and on eight, conventional, two-story houses (four of brick, and four of frame construction). Pressure-time histories were to be obtained of the blast at the distance of the houses, and at several other distances, as were ground shock measurements, and accelerations of several of the houses.

The site selected for this full-scale test was located in a remote section of the White Sands Missile Range, New Mexico. The tasks of building the site, and of evaluating the structural damage subsequent to the tests were assigned to the Corps of Engineers. The White Sands Missile Range provided complete technical photographic and timing instrumentation, obtained ambient meteorological data, and performed the assembly and special handling of the NIKE-HERCULES missiles.

7–5.3. (S) Test Facilities

The test facilities consisted of three underground NIKE-HERCULES magazines, twenty

houses (each of two stories), and six instrument shelters. The magazines and houses were arranged with four pairs of houses (one brick and one frame in each pair) located approximately 528 feet from the sides of each magazine, on lines normal to the sides. Two instrument shelters were located about 1.370 feet from each magazine, on opposite sides of the magazine. The overall arrangement of the three test sites is shown in Fig. 7–2. The frame and brick houses were identical except that the former had shutters on the front windows and doors. The houses were oriented with their front walls (longest dimension) toward the magazines.

The magazines were the U.S. Army Corps of Engineers special AAA underground missile storage magazines, type B. The internal dimensions of the magazines proper were about 62 feet by 62 feet by 13 feet high. The walls were of concrete one foot thick. Fig. 7–3 shows the floor plan. Tool racks, the hydraulic lift, and other items not contributing to this test were omitted.

The six NIKE-HERCULES missiles used for each test were complete with T–45 (blast fragmentation) warheads, sustainer motors, and boosters. The weights of the explosive and fuel contained in each missile are given in Table 7–2. The missiles were placed in the magazine in two groups of three, as shown in Fig. 7–3. Note, from the figure, that the warhead of the center missile of the left group was detonated statically.

TABLE 7–2 (S). APPROXIMATE EXPLOSIVE AND FUEL WEIGHTS OF THE NIKE-HERCULES MISSILE (U)

Component	Weight (lb)
Complete warhead	1,106
Warhead explosive (HBX–6)	650
Sustainer motor propellant	2,175
Booster motor propellent (Total cluster of four)	3,040

7–5.4. (U) Instrumentation

7–5.4.1. *General*

The air blast from the simulated accident was measured at a large number of stations, by several different techniques. Acceleration and displacement of the earth were measured at several stations on the second test, after the equipment was calibrated on the first test. A number of motion picture cameras recorded the response of the test houses to the effects of the blast. Auxiliary instrumentation included equipment for receiving coded time signals and for distributing these signals to all recording

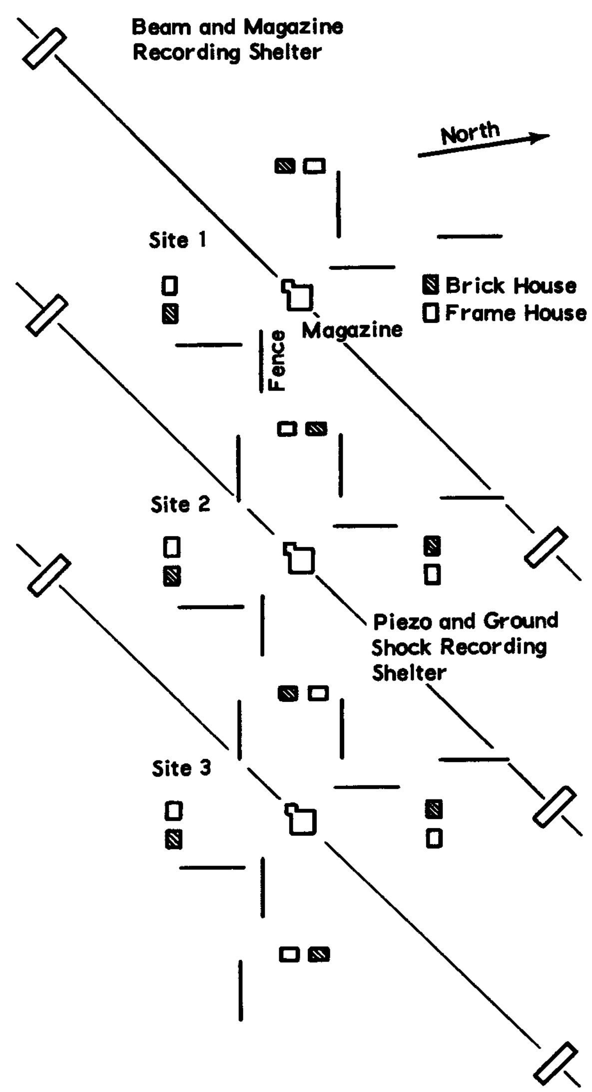


Figure 7–2. Plan View of NIKE-HERCULES Magazine-Safety Test Sites

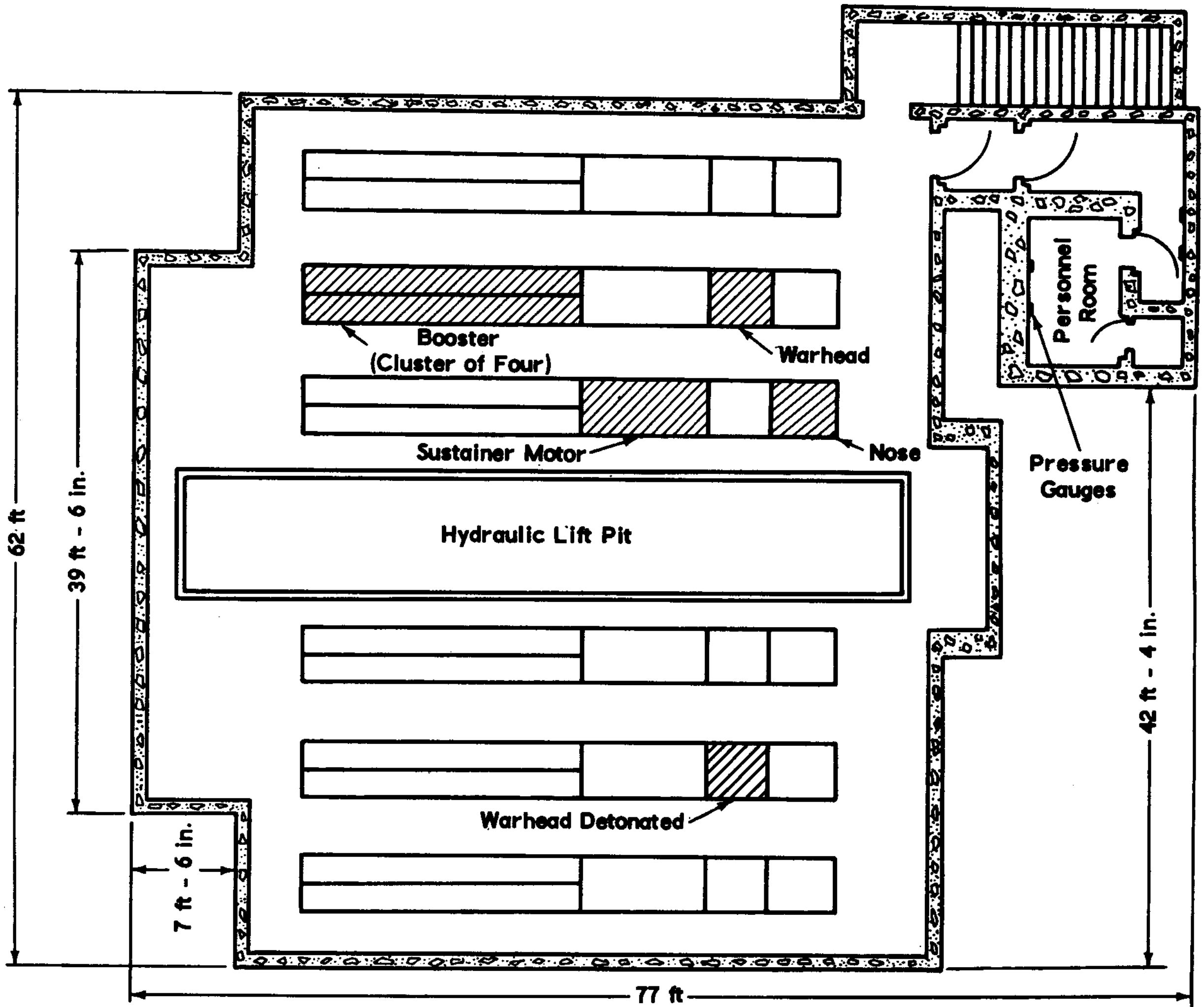


Figure 7–3. Layout of Magazine and Arrangement of Missiles for NIKE-HERCULES Magazine-Safety Test

equipment, and instrumentation for the measurement of meteorological conditions at the time of each test. The physical location of various instruments is shown in Fig. 7–4.

7–5.4.2. *Air Blast Measurement*

Five independent techniques were employed for measurement of the air blast waves generated by each test, as follows:

1. Measurement of the output of piezoelectric pressure transducers on a cathode-ray-tube oscillograph recorder.
2. Measurement of the response of mechanical pressure-time gages.
3. Measurement of pressures from strain-gage type pressure transducers on magnetic oscillographs.
4. High-speed motion picture photography of the outline of the shock wave against an interrupted background (a specially constructed fence).
5. Measurement of the response of slender cantilever beams to air blast.

The first three techniques yielded complete time histories of the pressure in the blast wave as it passed the gages. The fourth technique yielded data for estimating the velocity of the shock wave, and the last technique gave an

estimate of the effective weight of the explosive charge which generated the blast wave.

Two different types of piezoelectric gages were used, the Atlantic Research Air Blast Gage and the BRL Stressed Diaphragm Gage. The construction and operation of these gages is discussed in Ch. 4, Sec. I, Par. 4–5.6 and 4–5.3, respectively. Each gage signal was amplified by a direct-coupled, dc amplifier and displayed on a cathode-ray tube. (The frequency response of the dc amplifier used was flat, within 3 per cent, from zero cycles to 50 kc, within 10 per cent to 100 kc, and within 25 per cent to 150 kc.)

The traces on the cathode-ray tubes were photographed by optically focusing on photographic paper moving at 50 inches per second. Timing was provided by two means: an internal frequency standard which provided millisecond markers on the edge of the photographic

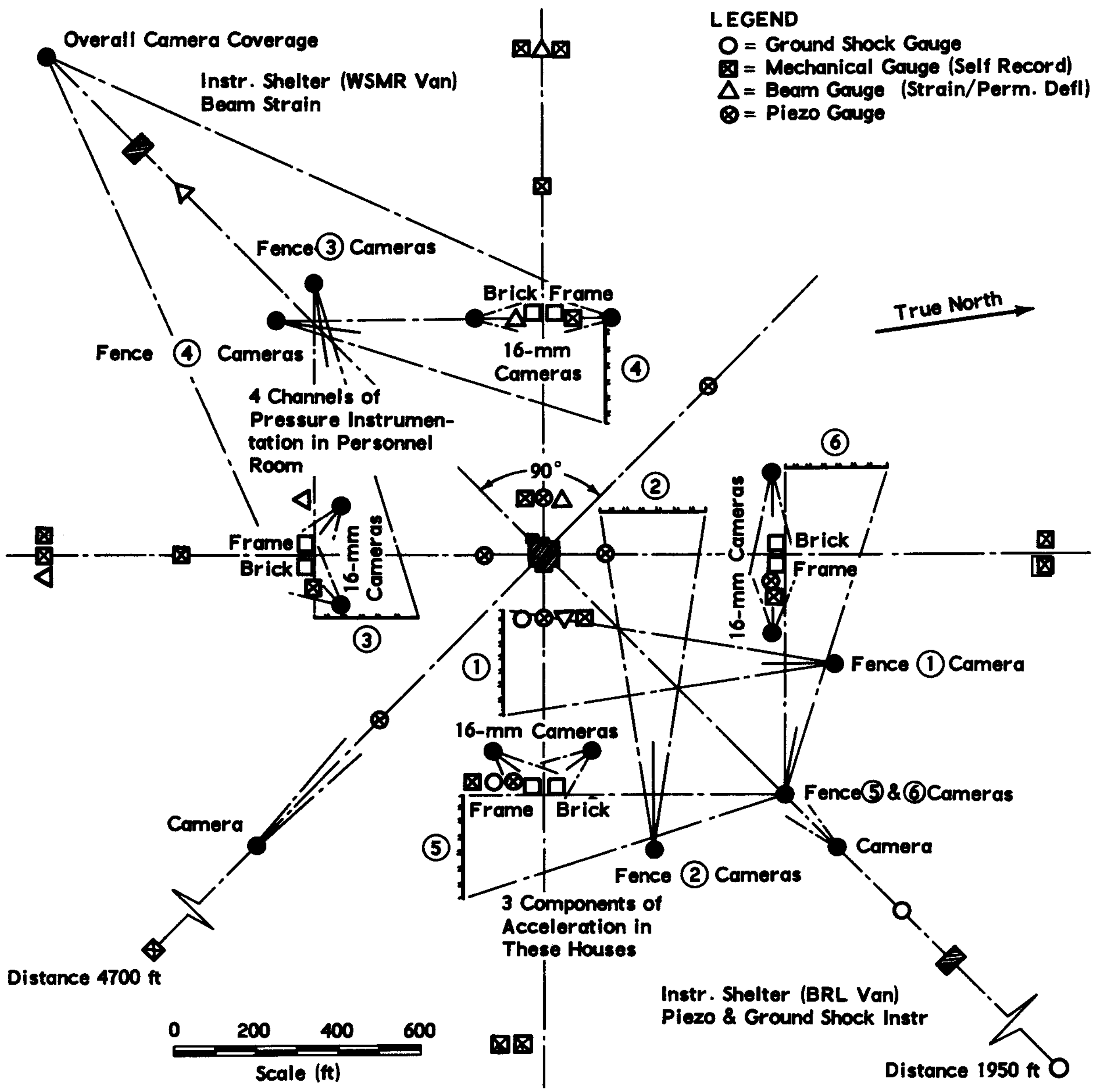


Figure 7–4. Instrumentation Layout for NIKE-HERCULES Magazine-Safety Test

record; and a coded, 1,000-cycle timing signal provided by White Sands Missile Range and displayed on one of the channels not used for gage recording.

The mechanical self-recording gages were of BRL design, and are described in detail in Ch. 4, Sec. I, Par. 4–5.5. They have a flat frequency response from 0–1,000 cps.

The commercial, strain-gage type, pressure transducers (Consolidated Type 4–312) and their associated magnetic oscillographs have an intermediate frequency response of 0–3,000 cps. They are fully described in manufacturer's bulletins.

Interrupted backgrounds (fences) for high-speed photographs of the shock wave were erected at a number of locations at each test site. The interrupted-background technique for measuring shock wave parameters, and the cantelever-beam gages, are discussed in Ch. 4, Sec. I, Pars. 4–5.1 and 4–5.7, respectively.

7–5.4.3. *Acceleration and Displacement Measurement*

Three mutually perpendicular components of acceleration, giving measurements in a vertical, transverse and radial direction from the magazine, were obtained in both the frame and brick houses located to the east of the magazine. Ground shock gages measured the acceleration and displacement of the earth.

Accelerometer measurements were made with variable reluctance accelerometers and the measurements were recorded with a 3-kc carrier recording system.

To measure vertical and radial displacements, seismographs constructed at BRL were used. The seismograph used to measure vertical motion was an astatized, spring-supported, vertical pendulum. Radial horizontal displacements were measured by a horizontal pendulum hinged to oscillate in a horizontal plane.

7–5.4.4. *Motion Picture Coverage*

A number of motion picture cameras photographed the test houses and the magazines. The majority of the cameras were arranged so that timing marks could be impressed on the edges of the film, allowing accurate measurement of the framing rate.

7–5.4.5. *Auxiliary Instruments*

The most important auxiliary instrumentation was the electronic time-signal equipment. This equipment received coded radio time signals from central facilities at White Sands Missile Range, and distributed them as voltage pulses over wire to the various oscillographs and cameras which recorded the test data. These signals allowed accurate correlation of the sequence of events in the tests, and also provided accurate time scales on all records.

Meteorological equipment at the test site consisted of a commercial recording aneometer which continuously measured wind direction and speed during each test. Air temperature, and wind direction and velocity, were also determined by radiosonde at intervals of 1,000 feet up to altitudes of 20,000 feet.

7–5.5. (S) Test Procedure

Prior to the actual test firings at the White Sands site, preliminary tests for checking the instrumentation were conducted at Aberdeen Proving Ground. These included several scale model tests, which will be discussed later, and development of the photographic method for observing the shock wave against a fence background.

Before the first actual magazine firing, a test shot was fired to check the time sequencing and proper functioning of all instrumentation. A similar instrumentation check was made prior to the second magazine test, with no explosives being fired, but a fiducial marker being applied mechanically.

Several hours prior to the test, the firing circuit and all instrumentation were rechecked, and then continuously monitored to assure readiness for firing. Five minutes before firing, the armed warhead was connected to the firing circuit by White Sands personnel. At the proper time during count-down, an automatic sequence timer was actuated to start all instrumentation and fire the charge. Fig. 7–5 is a time diagram showing the sequence of events.

Except for several instrumentation changes, the second test was conducted in a manner similar to the first.

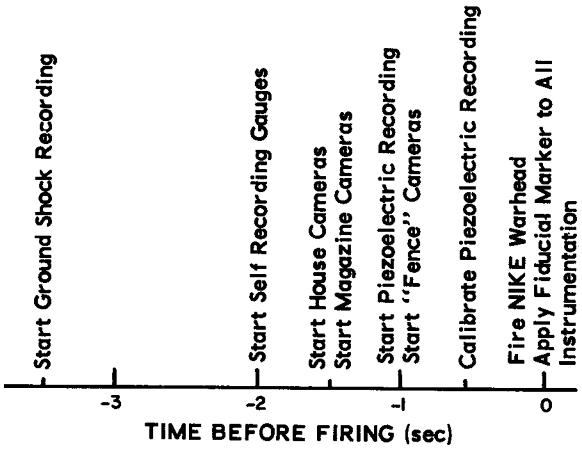


Figure 7–5. Sequence of Events for Firing NIKE-HERCULES Magazine-Safety Test

7–5.6. (S) Test Results

7–5.6.1. *General*

From the many measurements made in these tests, considerable shock data were obtained, for various orientations about the magazine, out to distances of approximately 5,000 feet. These data are presented in Ref. 4, in a series of tables and curves which present the results of the measurements as functions of distance from the sides of the magazine.

7–5.6.2. *Initiation and Reaction of Missiles*

The primary objectives of these tests was to determine whether or not the accidental detonation of one warhead would initiate other missile warheads and propellants, and whether or not the storage magazine could contain the possible resultant combined air blast sufficiently to prevent serious damage to the houses. The results show in both tests that more explosive detonated than was contained in the one warhead initiated statically. In addition, a quantity of the propellant, contained chiefly in the sustainer motors, probably contributed to the blast.

For the most part, the booster motors were contained in the magazine and burned. In the first test, one sustainer motor, partially propulsive, spun about and burned on the surface of the ground about 350 feet from the magazine. Almost immediately after the initial detonation, one booster motor was observed to fly over the houses for a distance of about 1,500 feet. The propulsive motor apparently exploded upon impact with the ground.

From evidence observed after each simulated accident, determination was made of the most likely sequence of events within the magazine. Details of these conclusions are given in Ref. 4.

7–5.6.3. *Magazine and Personnel Shelter Damage*

In each incident, damage to the underground magazine and adjacent personnel shelter was catastrophic. The roof of the magazine was blown completely off, and pieces of concrete and parts of the steel elevator doors were blown out to distances of nearly 1,200 feet. The only portions of the magazine structure remaining after the blast were the concrete floor and walls, which were badly broken and chipped from fragment impact. All of the walls were pushed back from the vertical, leaving a crater ranging from 110 to 120 feet in diameter. From an analysis of motion picture coverage of the magazine, it appeared that the initial blast loading on the roof of the magazine structure occurred from 6 to 8 milliseconds after the initial blast.

In both tests, the magazine personnel rooms were badly damaged, and they would have offered no protection to personnel who might have been inside.

In each test, the roof and underwalls collapsed, permitting earth over top of the magazine structure to either partially or completely fill the room, the access passageway and escape hatch.

7–5.6.4. *House Damage*

Damage to the main structural members of the houses apparently was minor. Damage from the air blast was limited for the most part to breakage of windows, doors, and rafters on the sides facing the magazine.

In the second test, motion picture films showed, at least in one case, that the entire side walls of the frame houses, and the roofs of all the houses, were deflected inward under the air blast loading. Further evidence of lateral motion of the walls was noted in the

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TABLE 7-3 (S). RESUME OF AIR BLAST DATA (U)

Distance from Magazine Wall (ft)	Peak Pressure (psi)		Positive Impulse (lb-msec./sq in.)	
	Test 1	Test 2	Test 1	Test 2
100	4.6	6.9	96.0	145.0
528	1.10	1.27	27.8	46.3
845	0.64	0.75	18.6	28.7
1170	0.45	0.52	13.7	20.8
2000	0.25	0.27	8.2	12.3
3000	0.16	0.16	5.4	8.0
4700	0.11	0.09*	3.3	—

NOTE:
* Extrapolated value.

considerable plaster damage that existed, especially on the side walls and the walls facing the magazine. More fragment damage occurred to the houses during the second test, particularly from large pieces of concrete either falling through the roofs or entering through windows.

7-5.6.5. *Air Blast Effects*

A resume of the air blast from each of the two tests is given in Table 7-3. In both tests, the times of arrival of the blast wave, measured at the 528-foot and 1,190-foot distances, indicated that irregularities in the initial blast wave had smoothed out, and that it was fairly symmetrical about the center of the magazine

TABLE 7-4 (S). SUMMARY OF GROUND SHOCK DATA (U)

Condition of Measurement	Distance from Explosion	
	100 feet	528 feet
Accelerations in ground due to:		
(a) True ground shock*	0.03g**	0.10g**
(b) Induced by air blast	1.60	0.37
Accelerations in houses due to:		
(a) Ground shock	—	0.33
(b) Air blast	—	30.0 (approx.)
Ground displacements due to:		
(a) Ground shock	—	0.020 inch
(b) Induced air blast	—	0.045 inch (approx.)

NOTES:
* Shock transmitted from the point of explosion, through the ground, to the point of observation.
** g is the acceleration due to gravity; 32.2 feet per second per second.

Chapter 8 (S)

AIRCRAFT

Section I (U)—Introduction

8–1. SCOPE OF THE CHAPTER

This chapter describes aircraft terminal ballistic data and the methods of collection and analysis of these data. A discussion of kill mechanisms in terms of aircraft damage is first presented. This is followed by consideration of damage to various aircraft components, in the light of experience gained from an operational and test environment. The methods of data collection and analysis are next presented in two separate sections: Tests and Data Generation, and Synthesis of Terminal Ballistic Data. The first of these presents an introduction to the physical experimentation and generation of data at the various ordnance proving grounds, and describes the nature of the testing procedures and the form of the resulting data. The second of these two sections introduces the methods whereby these test data are combined, adjusted, or extrapolated in order to provide appropriate information.

This information on the terminal ballistic parameters of aircraft configurations provides the tools for weapon systems and effectiveness studies. These studies apply the terminal ballistic data to combat situations, in order to evaluate aircraft kill and survival probabilities.

8–2. CROSS-REFERENCE INFORMATION

Ch. 3, Sec IV of the publication presents a discussion of the terminal vulnerability of the aircraft target, and of the means by which aircraft are killed and damaged. In addition, this previous section presents various fundamental considerations and definitions which are prerequisite to an understanding of the information in the present chapter. Where necessary, reference is made to Sec. IV of Ch. 3, and to other, applicable portions of the publication.

Section II (C)—Kill Mechanisms and Aircraft Damage

8–3. (C) INTRODUCTION

(U) A necessary preliminary to the study of aircraft vulnerability is a review of kill mechanisms in terms of damage that an aircraft might suffer in wartime. For the present purpose, it is sufficient to consider that damage to the aircraft is inflicted by one or more of the following fundamental actions: conventional blast, nuclear blast, fragmentation, or fire. The main factors which determine which of these actions cause the damage are the type and size of warhead, the nature of the target, and the accuracy of the delivery.

(C) A small aircraft rocket will, of necessity, be designed primarily to inflict damage by internal blast; weapons with warheads up to about 100 pounds in weight will probably be designed for optimum fragmentation effect; while over this weight, warheads may be designed for either external blast effect, fragmentation effect, continuous-rod projectors, or as "parents" for shaped charges or sub-projectiles. The selection of particular warhead characteristics would depend largely on the characteristics of the target to be attacked. For example, an aircraft with considerable speed and a very strong structure will probably be difficult to kill by conventional means, whereas a nuclear blast warhead could be more effective.

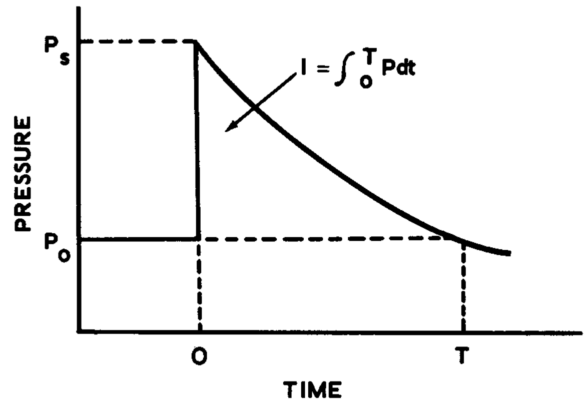


Figure 8–1. Pressure-Time History of a Blast Wave

8–4. (C) BLAST FROM CONVENTIONAL EXPLOSIVES

8–4.1. (C) General

(U) When the explosive detonates, the solid material is rapidly converted into a mass of hot, high-pressure gases. The surrounding medium is compressed by the expansion of these hot gases and propagates a blast wave. The pressure-time history of this wave is characterized by a sudden increase in pressure, followed by an exponential decay (Fig. 8–1). If the pressure in the blast wave is sufficiently intense, and if the decay is slow enough (i.e., the impulse or the integral of the pressure with respect to time is sufficiently large), then the blast wave can critically damage an airframe.

(C) In order to consider conditions that affect the magnitude of a blast wave, parameters may be selected which can be correlated with the deformation or destruction of the airframe. There are two such sets of parameters: peak pressure and positive impulse produced in free undisturbed air (i.e., with no reflecting or interfering surface present); and the peak pressure and positive impulse transmitted to an infinite rigid wall. Pressures and impulses measured in free air are designated as side-on pressures, and those measured on the surface of a rigid wall at 90° incidence are termed face-on pressures. These parameters are lower and upper bounds, respectively, of the crushing blast loads imposed on any structure, and target orientation is important in any attempt to predict the true blast loading. The term overpressure indicates that pressure which is over and above the ambient pressure, or, often, the ratio of resulting blast pressure to the ambient value. (For detailed discussion of these blast-effect terms, refer to Ch. 2, Sec. IV, and to Ch. 4, Sec. I, Par. 4–2.).

8–4.2. (C) External Blast

The results from actual external blast trials against aircraft indicate that it is possible to correlate damage with the peak pressure and positive impulse in the blast wave. Consider a range of explosive weights detonated near a target, at distances which result in the same level of damage for all the weights considered. Associated with each explosive weight and distance, there can be found a side-on and face-on peak pressure and impulse based on other experimental results. A plot of these pressures and impulses for a range of charge weights yields what can be termed damage threshold curves (Fig. 8–2), which provide an indication of these combinations of pressure and impulse necessary to do lethal damage to a particular target. Lethal damage distances for any intermediate explosive charge weight can be determined from such plots.

The blast curves described above apply only for the condition of the test, namely, for motionless aircraft, for stationary, uncased explosives, and for sea-level atmospheric conditions. Early studies at BRL, however, indicated that variations in ambient and/or test conditions had a decided effect on the blast

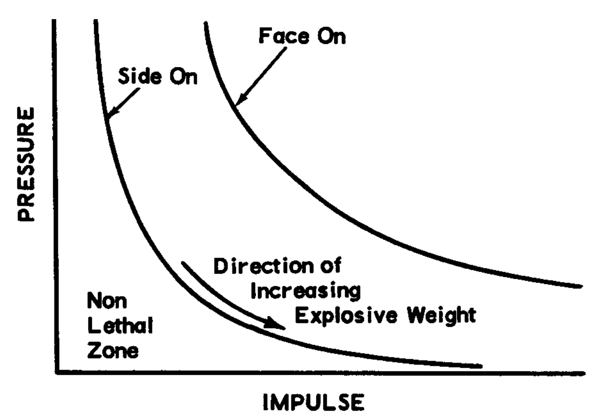


Figure 8–2. Damage Threshold Curves

parameters, which resulted in considerable changes in charge-to-target distances necessary to obtain lethal damage. (Fig. 8–3 illustrates those conditions that effect the propagation of the shock.) These observations led to a comprehensive series of experiments, supplemented by theoretical analysis, which have resulted in the development of methods for predicting the effects of variations in the conditions noted. These experiments are discussed in Par. 8–17, following.

The results of extensive, external-blast trials are available, with the data presented in the form of "damage contours," for various weights of explosive charge, drawn around the particular test aircraft. These contours represent distances inside which detonation of the specified charge weights will result in a specified category of damage. (For damage categories, refer to Ch. 3, Sec IV, Par. 3–15.5.) Because aircraft structures vary so considerably, it is difficult to extrapolate directly from one aircraft to another; therefore, each structural type must be treated more or less separately.

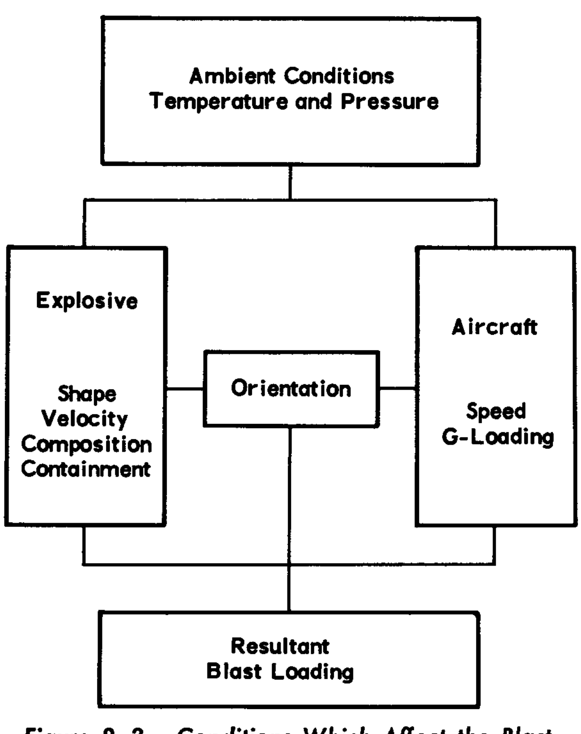


Figure 8–3. Conditions Which Affect the Blast Parameters

Altitude has a decided effect on the severity of external blast. The relationship of external blast damage to shock wave parameters, such as peak pressure and positive impulse, provides a means wherein this effect can be evaluated, because the effect of altitude on these parameters is well established. However, the procedure is complicated because of the two possible criteria of damage, one assuming a side-on pressure, and the other a face-on pressure. In either case, the blast effectiveness is materially reduced with increase in altitude over about 30,000 feet, but the reduction is less for face-on pressure. It has been suggested that side-on pressure should be used when the target subtends a small presented area to the blast wave, and that face-on pressure should be used when the target subtends a large presented area.

8–4.3. (C) Internal Blast

It is important to differentiate between internal and external blast. The former occurs when a high-explosive shell penetrates into the structure and detonates in an internal compartment. It constitutes an effective means of obtaining airframe damage. Such direct hitting projectiles may be either complete missiles or small sub-projectiles projected from a large, parent warhead. For both types, the form of damage is similar.

From the results of ground firing trials, considerable data has been accumulated regarding the effects of internal blast on aircraft structures. It has been found that explosive projectiles are most effective when detonation is delayed until the projectile is fully inside an aircraft structure. Because the violence of the blast effect associated with any projectile must be related to the weight of explosive charge, this weight is usually taken as the criterion of the severity of the blast effect.

Efforts have been made to correlate the damage effect of a projectile with its total energy (the sum of the kinetic and chemical energies), but this principle appears to hold good only for a limited class of projectiles. Data from field trials are presented in the form of vulnerable-areas, cross-hatched on a dimensional sketch of the particular aircraft tested. This cross-hatched notation will indicate the weight

of bare charge (usually located 6 inches under the skin) necessary to produce a specified degree of damage at a particular location in the aircraft.

The effect of altitude on internal blast has been fairly well established. It is designated as the increase in charge weight necessary to inflict a given degree of damage at varying altitudes. If it is assumed that the criterion for inflicting lethal damage (be it peak pressure, positive impulse, or a combination of both) is independent of altitude, it is possible to modify the results of ground trials for the effects of altitude.

8–4.4. (C) Fragmentation Effects of Explosive Projectiles

In addition to the blast effect, explosive projectiles can damage components by fragmentation effects. Fragments are projected within fairly well-defined limits, depending on the shape of the projectile, the casing thickness, and the striking velocity. The area vulnerable to fragment damage around a component may be larger than the area vulnerable to blast damage. For example, a shell may burst near a pilot, but not near enough for blast damage to be lethal; however, the fragment spray may reach the pilot and prove lethal.

8–5. (C) BLAST FROM NUCLEAR EXPLOSIONS

(U) The airplane subjected to a nuclear air burst at close proximity will normally be completely disintegrated, resulting in what may be termed an "over-kill." However, at a distance from the actual point of detonation, the nuclear blast results in the following three separate types of effects on the airplane structure: blast pressure, gust attack concurrent with the shock wave, and thermal radiation (Ref. 1). In addition, there are radiation hazards to the aircraft personnel.

(C) The blast pressure can be considered as an impulsive load caused by the instantaneous application of the peak overpressure. The duration of this type of loading is usually not sufficient to cause the build-up of large stresses in the primary structure. The rapidity with which the shock wave envelopes an airplane surface, such as a wing, is such that the pressures are almost instantaneously equalized on both sides. Thus, the overpressure does not affect primary structure; but it is dangerous to elements such as bomb bay doors, access doors, windows, control surfaces, or other relatively unstiffened or unsupported panels. For certain positions in space relative to the bomb burst, however, this phenomenon can be more critical than the gust problem, particularly with small yield weapons.

(C) The gust loading is that imposed on the airplane immediately following passage of the shock wave, and is due to the material (particle) velocity behind the shock wave. It is similar to the commonly known atmospheric gust attack, except for its intensity. The shock wave travels at a speed somewhat greater than sonic velocity, and has a very high energy level and a very short application time. It imposes a very intense, dynamic, sharp-edged gust which begins at a high, positive, subsonic velocity and then decays with time, passing through zero velocity and on into a negative phase. It attacks the airplane as a typical gust, causing translation of the airplane, and inducing loads in the primary structure. Ordinarily, it is of such duration that it does not cause large rotations of the aircraft due to passage across wing or tail surfaces. For the larger weapons, the gust possibly acts at a time when the aircraft structure is still heated from the thermal phase, and the dynamic response to this gust loading can result in a primary structural failure.

(C) The thermal radiation energy transmitted to the aircraft structure is that existing at a given point in space due to emanation from the explosion and from the resulting fireball. It is a direct function of the size (yield) of the weapon, the distance from the explosion, the atmospheric conditions, and many other factors. It travels at the speed of light and, hence, it must be the first effect to be considered on the airplane. In some cases the structure has been heated and cooled before the shock wave strikes; in other cases the thermal radiation is of a sufficiently long duration that combined thermal and gust effects on the structure must be considered. From the structural standpoint, the two main considerations are

the occurrence of thermal stresses, and the reduction of material strength. Secondary structure and components which can burn at low heat input are extremely vulnerable to the thermal radiation, and their damage or destruction can directly or indirectly cause loss of the airplane. These items include fabric or rubber coverings and seals, wiring and electronic equipment, radomes, antennas, windows, and like items, which either are temperature-critical themselves or allow internal components to be exposed to the radiation.

8–6. (C) FRAGMENTATION

Fragmenting warheads may be designed so that the warhead casing breaks up into fragments of natural or pre-determined sizes. (Fragmentation is discussed in Ch. 2, Sec. I, and in Ch. 4, Sec. III.) The use of natural fragmentation is largely obsolete, because a relatively large percentage of the casing of such warheads or projectiles is liable to disintegrate into tiny fragments (or dust) which have a rapid fall-off in velocity and very little penetrating power. The term of fragmenting warhead is now reserved for those which break up into fragments of controlled size and weight. These controlled fragment shapes may vary from cubes or rectangles of 1/64 to 1/2 ounce in weight, to rod-like fragments, the sizes of which are governed largely by the size of the warhead (these later warheads are known as rod fragmenting warheads). To distinguish the rectangular fragments from the rod-like fragments, the former will be referred to as small controlled fragments (Ref. 2).

It may be stated that, in general, all forms of airframe structure are invulnerable to single fragment hits from small fragments in the shape of cuboids. A fragment with sufficiently high velocity striking a structure of ductile material will penetrate and leave a fairly clean hole, which will not greatly exceed the dimensions of the fragment if the hit is nearly normal. Impact at small angles of obliquity may lead to rather more extensive damage, of a tearing nature, but still be of sufficient significance from a vulnerability viewpoint. Certain materials with extreme strength properties may shatter when penetrated by fragments, but the indications are that the majority of the materials used in aircraft structures will remain intact.

In order to inflict lethal damage on an aircraft, therefore, small, controlled fragments must "kill" certain components. Some components of an aircraft which may be vulnerable to such fragments are the pilot(s), engine(s), and fuel tanks, and possibly the pressure cabin enclosures in high-altitude flights. For a single-engine, single-seated aircraft, the chances of inflicting lethal damage could be high, because only the pilot or engine needs to be killed. Depending on the size and velocity of the fragment, and on the type of fuel tank, a small fragment will cause a loss of fuel (and could cause a fire) which may result in a delayed kill on the aircraft. (Damage category B: refer to Ch. 3, Sec. IV, Par. 3–15.5 for damage categories.) Against a multi-engine aircraft, fragments have a much reduced chance of a kill. In general, at least one-half of the engines must be killed.

Under high-altitude flight conditions, pressure cabin enclosures may become vulnerable to fragments. On bombers, for example, fragments penetrating windows will possibly result in a loss of pressure, forcing the aircraft to fly at a lower altitude; thus the aircraft may not be able to return to base. On fighters, the penetration of the canopy by a fragment could result in complete shattering, followed by disabling of the pilot and loss of the aircraft. This would depend on canopy material and on the ambient conditions at the time of attack. The effects on the aircraft would of course be modified if the crew were wearing pressure suits.

It is possible for even a large number of small fragments to cause no more damage than the inflecting of a number of small holes. However, if the same weight of metal were combined in a smaller number of the long, rod-like fragments, critical damage could occur. The resistance of the aircraft skin to penetration by one of these projectiles would be much less than the total resistance to a number of small fragments, with the same total weight, because the shearing area would be reduced (the total surface area of the rod-like frag-

ments would be so much less). The term rod-like is used to refer to fragments varying from about 3 inches long, by 1/4 inch square cross-section, to the maximum size that can be fitted into a warhead.

The size of the rod determines to a large extent the type of damage inflicted on an aircraft. Small rod fragments up to 6 inches long by 3/8 inch square cross-section will not, in general, inflict lethal structural damage on an aircraft. However, they can cause destruction of fuel tanks by pressure-wave action if they strike at sufficiently high velocity; and on light structures they can result in wide-spread skin damage. These fragments may also have a high fire-raising potential. Larger rods can inflict lethal structural damage, the capacity for so doing being determined by the dimensions of the rod and the structure being attacked.

A most effective form of this type of warhead is known as a continuous rod warhead, formed of a series of rods welded end-to-end. The rods are ejected in the form of a continuous hoop, causing more severe damage than that inflicted by a number of individual rods of the same total weight.

Experiments with high velocity fragments have revealed that large and brilliant flashes occurred when aluminum plate box targets were impacted by fragments having velocities in excess of about 5,000 ft/sec. Considerable bulging and tearing of target sections, as though from an internal explosion, accompanied these flashes. This phenomenon is classed as vaporific damage.

Shaped charges, i.e., lined-cavity explosive charges, are one form of weapon capable of producing a stream of hypervelocity fragments which inflict vaporific damage to enclosed structures. As indicated above, the resulting damage is similar to that caused by internal detonation of a high-explosive charge. Trials have shown that, under favorable conditions, shaped charges are capable of inflicting lethal structural damage to aircraft, the degree of damage in part being a function of the charge liner material and the design, the standoff distance, the target construction, and the closing velocity and engagement altitude.

8-7. (C) FIRE

In the extensive literature on fuel-fire and its relationship to aircraft vulnerability, there has been, and still exists, an unfortunate confusion in terminology. In the following discussion of fire in relation to aircraft damage, such terms will be defined and explained.

"Combustion" or "burning" usually implies the chemical change(s) due to the mutual reaction of the constituents in a heterogeneous mixture of gases. The "combustion" reaction produces heat and light, these being emitted primarily from a zone called the "flame."

Where a "burning" fuel is in solid or liquid form, it is the vapors from the fuel that support the flame. Assuming no large scale turbulence, the flame is also fed by diffusion from the ambient reacting gas(es).

Another condition is that in which the fuel is mixed with an enclosed gas, and at least part of the fuel is in a gaseous state. If such a mixture is subjected to the action of an ignition source at a particular point, and the small, local volume around the source begins to burn, the particular mixture is said to be "ignitable" with regard to the particular pressure and temperature, and the particular ignition source. If the mixture is also "flammable," the reaction proceeds at a rate just sufficient to overbalance the loss of heat from the initial, local volume around the ignition source. As a result, the next layer of the gaseous mixture begins to burn, then the next, etc. Eventually, the flame is propagated throughout the gaseous mixture, the flame surface at any instant being called the "flame front." Note that all "flammable" mixtures are "ignitable," but that the converse is not true.

The range of pertinent parameters over which a particular gaseous mixture is flammable is termed its "flammability limits."

Owing to the time-increase in pressure that accompanies combustion (the pressure being a maximum at the flame front at any instant), the continuously increasing pressure gradient causes corresponding increases in the flame front velocity. The unburned gases ahead of the front undergo concurrent increases in

compression. If this compression reaches a critical value, the flame front velocity increases greatly (velocities on the order of $10^3 - 10^4$ ft/sec.) and a "detonation" or "explosion" is said to occur.

"Explosion limits" or "detonation limits" represent the range of pertinent parameters over which a particular gaseous mixture is "explosive"; i.e., capable of supporting an explosion. A "limit" mixture is one which lies in the range between "flammable" and "nonflammable" conditions, or between "explosive" and non-explosive" conditions.

A "fire" may be defined as the condition resulting from the ignition of a flammable mixture, in which the flame front velocity is on the order of 10 ft/sec. or less. (If not restricted to enclosed mixtures, the definition would include "essentially static flames.") By definition, the propagation of flame through a flammable mixture need not be "explosive" in nature.

It might well be pointed out that, in textbooks on the subject of combustion and related phenomena (as differentiated from the fuel-vulnerability literature), the word "explosive" is usually used to denote gaseous mixtures which are within the limits of flammability; i.e., "explosive" and "flammable" are considered to be essentially synonymous. Further, the phenomenon involving the supersonic propagation of a flame front is usually called a "detonation," and not an "explosion."

In fuel vulnerability literature, the word "explosive" has not been used as a synonym for "flammable," in that the word "explosion" appears to have definite connotations for the aircraft vulnerability analyst or researcher. For the same reason, the words "detonation" and "explosion" have been used interchangeably.

Although differentiation between the conditions leading respectively to "fires" and "explosions" in the air combat situations does not lend itself to simplification, immediate explosions ordinarily occur only when a cell is hit above the fuel level, and an explosive mixture exists in the space above the fuel; or when large-scale disruption of a cell occurs because of the detonation of a rocket warhead or HE shell. However, where liquid fuel is present, fire will almost inevitably follow an explosion (Ref. 3).

Additional terms meriting definition are "fuel-air" mixture, "dry" and "wet" hits, "mist," and "diffusion" flame. A "fuel-air" (F/A) mixture consists of fuel vapor and air. In much of the literature it is assumed to be in the saturated, equilibrium condition. That is, the temperature of the mixture is that of the fuel, the temperature of the fuel is that of the ambient air, the total pressure of the mixture is that of the ambient atmosphere, and the vapor pressure of the fuel vapor it at its saturated value. "Dry" hits are hits above the fuel level of a fuel tank or cell; "wet" hits are hits below the fuel level. "Mist" is finely divided spray. A "diffusion" flame is one burning in the vapor zone above a liquid fuel surface.

The "fires" encountered in aircraft vulnerability testing have been classified as follows (Ref. 4):

1. Fires fed by seepage (so-called "candle fires"). These are of relatively long duration, but never cause A or B damage. They are more prevalent for gasoline than JP–1 (jet engine fuel).
2. "Flash fires." These are fires which last only a few seconds, and no explosion occurs.
3. Fires fed by leakage. These differ from "candle fires" only in degree of leakage, but are the most serious form of non-explosive fire.

Section III (C)—Aircraft Component Damage

8–8. (U) INTRODUCTION

The vulnerability of a given airplane is determined from the appropriate summation of the vulnerability of its component "parts." Certain damage mechanisms are of more significance than others with respect to specific component "parts." Separate paragraphs discuss each of these "parts" and the applicable

damage mechanisms. Much of this information was taken from Ref. 5.

8-9. (C) AIRFRAME DAMAGE

The structure (airframe) of an airplane has the largest presented target area, and lethal damage to it usually results in an instantaneous type of kill. The vulnerability of structure to various lethal mechanisms was briefly reviewed in the previous section, where it was indicated that internal blast constitutes one of the more effective means of obtaining structural damage.

The results of tests in this country and in Great Britain indicate that, everything else being equal, to cause a given amount of damage, a high-explosive shell detonated outside the structure requires about three to four times the explosive required by a shell detonated inside the structure. Internal detonation requires, of course, that the shell be equipped with a delay-type fuze.

Internal blast damage tends to decrease as the structural compartment volume increases. It is not clear what the relative importance of the volume of a compartment is as opposed to its dimensions, although probably the minimum dimension is most important for elongated shapes. The use of blow-out panels to increase internal volume, when a detonation occurs, has been suggested, but there is presently some doubt that they can function quickly enough to provide relief.

The type of firing, static or dynamic, is of some significance. It has been noted that a given charge weight produced more damage in a dynamic firing than in a static detonation. For example, in test firings of aircraft rockets against B-26 and B-29 structures, the dynamic firings caused slightly greater damage than that produced by tests using statically detonated charges of corresponding weight and composition. (See Par. 8-17.5.)

Another factor that has been given consideration is cased charges compared to uncased charges. It is generally agreed that the presence of a casing decreases the blast wave strength below the bare charge value. However, it appears that, for detonation in a relatively small volume compartment, the net damaging effect of the charge is not materially altered, even with a casing of appreciable thickness. Any loss of air-blast effectiveness tends to be offset by the kinetic energy of the casing fragments. Where detonation occurs in a relatively large volume, significant damage from fragments (and the expanding gases) is largely obviated. That is, the fragment density at impact with the compartment walls has decreased to a negligible value. Under such conditions, the effect of the casing is to decrease the damage.

Although the basic type of construction for United States Air Force airplanes is still the semi-monocoque, there has been a trend toward shallow, thick-skinned wings, and the use of the more brittle alloys like 7075-T6 Aluminum and magnesium. The design methods attendant with these materials has led to an increase in internal blast vulnerability. At the same time, however, the probabilities of ricochet, "fuze-wiping," and fuze malfunction have been increased.

Some evidence exists as to the effect of monocoque construction. Tests with the all-magnesium and nearly full-monocoque D-558 Skystreak indicate that vulnerability to internal blast increases with the amount of monocoque.

Recent tests with the B-47 wing indicate that the thick skin tends to confine the blast to the interior of the wing, resulting in considerable spanwise damage to the internal structure. Skin bulging was not the governing damage. The wing also exhibited sensitivity to relatively small changes in the weight of high explosive; e.g., a one-fourth-pound charge in one portion of the spar box did very little damage, yet a one-half-pound charge in the same area completely destroyed the spar box.

Firing tests have indicated that fasteners and skin splices are critical items in regard to internal blast damage. Splices show a decrease in vulnerability when properly reinforced. Fastener lines, if they hold rigidly to a frame, tend to pull the frame away with the skin. On the other hand, if they are weak in tension, damage to the airframe is lessened, but aero-

dynamic performance may be decreased by the loss of large areas of skin.

Due to their size, construction, and function, the most susceptible volumes of an aircraft to internal blast are usually the fuselage, just forward of the tail surfaces, and the inter-spar wing compartments.

There exist wide differences of opinion concerning the ability of an aircraft to fly with a specified amount of damage to the tail surfaces. Because of their relatively light construction and small compartment size, they are subject to damage by even small HE rounds, but because no common opinion exists as to the damage required for lethal results, conclusions are largely subjective. It may be that the amount of damage required for loss of control is a function not only of the detail design of the individual airplane, but also of its loading conditions at the moment of hit, and of the maneuverability subsequently required. During World War II, some aircraft returned with tail surfaces almost entirely missing; however, it is probably safe to assume that these constitute exceptional, rather than average, cases. A fairly common assumption would be that loss of one horizontal stabilizer and/or one elevator is not lethal, but that loss of both horizontal stabilizers is lethal. Loss of both elevators is considered to be lethal in most instances. It is fairly well agreed that the loss of the rudder is not lethal, and that even if a considerable portion (50 per cent of the area) of the vertical fin is gone as well, the damage will not be lethal.

The forward section of a bomber fuselage is vulnerable to blast for two reasons: because it contains the most necessary crew members; and because it contains the origination point for the actuation of the flight and equipment controls. In most cases, the personnel vulnerability is more easily evaluated than that of the controls. Consequently, personnel vulnerability is usually given the most consideration.

The portion of the fuselage most resistant to blast is generally at the wing attachment points, because of the large diameter of the fuselage at these points, and also because of the strength of the structure required to transfer the wing loads.

The vulnerability of aircraft wings varies in roughly the following fashion. The required charge weight for lethal damage decreases, starting from the root and proceeding outboard, until about the three-quarter, semi-span point, where it begins to increase again. Because aircraft can fly with part of the wing outer panel missing, larger charges, again, are required outboard of the three-quarter semi-span point to remove enough wing to be lethal.

Chordwise, the least-critical damage is done by a charge detonated in the trailing edge section. The next least-vulnerable portion is the leading edge section, forward of the front spar.

The damage to the airframe of an aircraft as a result of conventional fragment hits is negligible. In thousands of fragment hits observed at Aberdeen Proving Ground, there is no record of *A* or *B* structural kills (Ref. 6). It is possible that a high concentration of fragments in a small area, on some main structural member, could cause a structural kill. However, as this would imply either a direct hit, or near miss, the blast would probably be the damaging medium to be considered, or the fragment density over the entire aircraft would be high and kill of other components would occur.

The oxygen and hydraulic systems are usually considered as components of the structure. A hit on the hydraulic system will cause the loss of the equipment for which the system is a part. In addition, it will feed any fire that may already exist. The fluid itself is not readily ignited. However, if the oxygen and hydraulic systems suffer damage in the same locality, the resulting conflagration can kill the aircraft.

The previous discussion of external blast damage (Pars. 8–4 and 8–3) applies directly to the airframe component. One observation of interest made from the experimental data is of use in manipulating tests data. This is that the ratio of the enclosed areas of the explosive-charge damage-contours for 450 pounds and 1,000 pounds, in any particular plane through a target aircraft, remains essentially constant for all types of aircraft (Ref. 7). Tests also reveal that in general the control surfaces may be jammed by a blast wave too weak to damage

them structurally, and that bomb bay doors tend to exhibit relatively high vulnerability to external blast.

8–10. (C) AERODYNAMIC AND AEROELASTIC DAMAGE

Aerodynamic kills of aircraft result from damage-induced or blast-wave-induced changes in the airflow pattern which could result in loss of controllability, lowering of performance, etc.

Aeroelastic kills result from damage-induced decreases in the ability of the airframe to resist flight loads, e.g., flutter due to a damage-induced decrease in the critical speed, failure of the airframe under flight loads, etc.

Because most firing tests make no provision for the application of simulated airloads, some aerodynamic or aeroelastic kills may pass unnoticed. It is understandable that a kill due to a damage-induced decrease in critical flutter speed, or due to an increase in drag, usually is not obvious in ground tests.

In an effort to make damage assessments more realistic, as well as to gain a better understanding of the phenomena involved, analytical work on aerodynamic and aeroelastic vulnerability has been performed by the Cornell Aeronautical Laboratory, and by Biot and Arnold (Refs. 8, 9, and 10). It has been determined that combat damage to an aircraft will cause a drag increase by: the change of momentum of the leak flow, the change of momentum in the boundary layer flow, and induced drag due to redistributed lift.

Missions requiring that aircraft be employed at their ultimate performance capabilities render them susceptible to "C" kills. It has been estimated that the drag of a "clean" fighter is doubled by holing from one to six per cent of the wing area. Any drag increase of this order could cause a "C" kill on a high-performance interceptor, provided it was hit sufficiently early in a "pass," and that its margin of speed was relatively small. Also, with regard to a high-performance turbojet bomber, holing of one to five per cent of the wing area, if it occurred before the bomber was half-way to the target, would prevent the aircraft from reaching its target and returning to base.

Although experimental evidence is meager, it appears that aerodynamic damage sufficient to cause loss of aircraft controllability will ordinarily be so sever that other causes will contribute to the kill of the aircraft. For example, the damage required to overcome aileron control is estimated to be 10 to 30 per cent loss of the total wing area for a fighter, and 7 to 15 per cent for a bomber.

Elevons are more vulnerable than separate elevators and ailerons. The loss of one elevon will cause loss of control. Damaged ailerons, on the other hand, can be aided in their functions by the use of the rudder.

With regard to the loss of contour skin, there has been some concern over progressive skin peeling after damage is incurred at high airspeeds. However, experimental evidence indicates that tear lines tend to converge rather than diverge, thus limiting the area of damage.

Attempts to study the damage-induced failure of wing structure in an analytical manner have thus far yielded only the broadest of generalities, due to the complexities involved. Even where simulated airloads are applied to wings damaged in firing tests, the simulation is incomplete. Gust loads, maneuver loads, etc., are dynamic in nature. The strains produced by a dynamic load may be twice as great as those produced by a gradual application of the same load, and may be tripled in the case of a suddenly reversed load.

At the so-called critical flutter speed, a small speed increase will cause vibration amplitudes to increase rapidly with time, leading to structural failure. Biot and Arnold have investigated damage-induced flutter in aircraft with straight wings, and with engine(s) either in or adjacent to the fuselage. It was concluded that for such aircraft, damage-induced flutter may be neglected in a vulnerability evaluation.

The critical flutter speeds of fixed tail surfaces, due to the torsional rigidity of these elements, are sufficiently high to contribute no areoelastic vulnerability. Aileron flutter can be obviated (i.e., no finite critical speed then exists) by proper counterweighting. In the case of wing flutter, however, there is always some critical speed. By increasing the wings'

torsional stiffness, this critical speed may be raised. But as aircraft wings become thinner, and as speeds rise, the margin of safety between operating and critical speeds narrows.

It should be evident from the summarized coverage just given that quantitative data on aerodynamic and aeroelastic vulnerability are meager. In attempting to link aerodynamic theory with combat damage, one is grappling with exceedingly complex phenomena. For example, a mere scratch on a laminar flow airfoil may cause a drag increase, whereas certain moderately sized wing holes have been found to decrease drag. In addition to this complexity, some of the obstacles to a better understanding of aerodynamic and aeroelastic vulnerability are: the lack of proper testing facilities; fragmentary knowledge of transonic aerodynamics; and the unsettled state of supersonic aircraft design, in regard to both configurations and propulsion systems.

8-11. (C) FUEL-FIRE DAMAGE

Although aircraft carry more than one flammable material, the only one which is carried in sufficiently large quantities and has a large enough presented area to give a high chance of killing the aircraft is the fuel system. The initiation of a fire in or near a fuel tank can only be caused by the ignition of a flammable mixture. A discussion of the ways in which this can happen, as well as other considerations, follows.

Fuel-fire is a complicated problem even for commercial aircraft, where fires occur only by accident, rather than as the result of attack. For military aircraft engaged in combat action, the problem is especially complex. In fact, it is generally agreed that analyses of the vulnerability of the fuel system at tactical altitudes remains the most difficult problem in aircraft vulnerability.

The state of knowledge is especially critical with regard to the likelihood of fuel fires at altitudes over 30,000 feet. In addition, the fuel-fire kill is unique in that the aircraft necessarily carries the energy for its own destruction. The statement of this problem perhaps is best expressed in a direct quotation from Ref. 11. "It is a problem in weapon design to provide the most effective trigger for this energy, a passive defense problem to prevent the destructive release of this energy, and a vulnerability problem to know under what conditions the one will prevail over the other."

It appears from World War II operational data that at least half of all aircraft lost by the belligerents were killed by fire (Ref. 12). In the years since 1945, additional operational data on fire lethality have come from Korean combat reports and United States Air Force accident reports. Although the conditions under which aircraft accidents occur are generally not equivalent to combat conditions, these accidents do occur in actual flight, under the influence of airflow, airload, and crew psychology factors difficult or impossible to simulate in ground test firings (Refs. 13 and 14).

It has been observed that a 20-mm, M97, HEI shell, detonated statically within a gasoline-filled, B-17 fuel cell will not cause a fire, and that an M97 shell detonated statically outside a cell may not (depending on the test geometry and target) cause even leakage. However, if the shell is located in the cell wall, a fire will result (Ref. 15).

In dynamic firings of 20-mm shells, fires have been obtained with detonations outside the cell; although, the 20-mm shells detonated dynamically inside a gasoline-filled container did not cause a fire. With the detonations outside the cell, a directional effect due to the angularity of the line of fire and resulting fragmentation has been noted (Ref. 16). It appears valid, therefore, to assume that casing fragments are important in initiating fire. Further evidence comes from the observation that bare charges detonated statically in contact with the skin, directly over or under a fuel cell, can cause fire, because the skin produces fragments.

In the case of dynamic firings, the particular round, fuzing, target, purging system (if any), attack aspect, and impact velocity will determine the relation between the probability of a fire and the distance from the cell to the point of shell detonation.

A one-pound bare charge of TNT detonated inside a gasoline-filled cell will demolish it, but

will not cause a fire (Refs. 15 and 17). Because slower-burning black powder would give temperatures greater than the ignition temperature of the spray emerging from a disrupted cell, it would be expected that one-pound black powder charges detonated under the same conditions as the TNT would cause a fire. However, tests have shown that only leakage results.

A small inert fragment or bullet may cause a fire outside a fuel tank. A hit on an aircraft skin will ordinarily produce a flash, both internal and external to the skin (Fig. 8–4). These flashes tend to form within one millisecond and to die within two milliseconds after the impact.

The flash is thought to be due to the vaporization of fine aluminum particles. According to the hypothesis advanced by the New Mexico Institute of Mining and Technology, the impact of a fragment on the skin produces many fine aluminum particles with clean surfaces. These particles oxidize so rapidly that the heat generated is sufficient to raise the temperature of some of the particles beyond the boiling point of aluminum (1,800° C) or aluminum oxide (2,250° C). As the oxidized surfaces boil off, and/or are broken off by boiling beneath the oxide skin, the process proceeds as an aluminum vapor fire.

The flashes on both the entry and exit sides emerge from the plate at approximately the striking velocity of the fragment. The fragment ordinarily enters the fuel cell within one millisecond after the skin impact, causing a spray-back of rubber particles (if the cell is of the self-sealing type) at about the velocity of the fragment, within another one-fourth of a millisecond. About two milliseconds later, fuel spray emerges at approximately 200 to 300 ft/sec., and may be ignited by the flash or by the rubber particles themselves. The latter tend to act as intermediate tinder. When the striking velocity is sufficiently high, a secondary flash volume may occur, immediately adjacent to the tank wall.

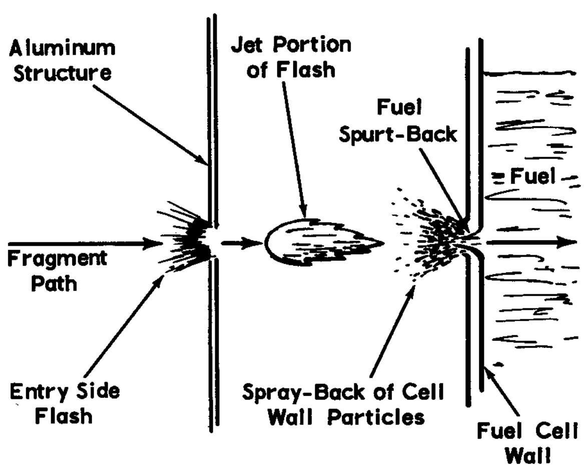


Figure 8–4 (C). Inert Fragment Fire Initiation, Simplified Diagram (U)

Relatively thick aluminum plates produce large flashes, but on the entry side only. Thin plates tend to produce little flash on either side. Plates of intermediate thickness usually produce sizeable flashes on both the entry and exit sides. The amount of flash is influenced by the fragment material, shape, roughness, striking velocity, and availability of oxygen (altitude).

In general, the probability of a fire from fragment impact increases with increase in fragment velocity, and weight. At striking velocities below 3,500 ft/sec. (approximately), the fragment orientation at impact also appears to affect the probability of a fire. This probability is also affected by the following characteristics of the fuel cell: self-sealing properties, inflammability of the ejected cell-wall particles, ability of the cell wall to absorb flash, and rigidity of the cell walls.

"Pyrophoric" fragments, i.e., fragments containing spark-producing materials, do not depend on the oxidation of aluminum particles. Tests with pyrophoric fragments provide a number of data (Ref. 18). The fragments produce a much larger and different type of energy source than do non-pyrophoric fragments. The sparks are consistently large, and the size of spark increases with the amount of pyrophoric material and is little related to the oxidation of the target skin particles. In addition, sparking can be produced at lower velocities than those at which a non-pyrophoric fragment can cause flash, and sparking size and duration tend to decrease with increasing altitude, but are still significant at 60,000 feet.

The initiation of fuel tank fires by rod frag-

ments is governed by a sequence of events similar to those occurring with small inert fragments. Rod fragments have an advantage, however, in that the flash produced is much larger and persists for a longer time, and greater quantities of fuel are released. Rod fragments may also be designed specifically to attack fuel tanks. For this purpose the rods are drilled and the cavities are filled with incendiary agents. By this means, the source of ignition can be deposited outside the fuel tank and persist for a relatively long period. A further advantage claimed for rods over small fragments is that they can defeat fuel tanks which are purged with inert gas, because the damage inflicted is large enough to allow inlet of sufficient air to support combustion.

Small, direct-hitting projectiles, especially when containing an incendiary element, can initiate fires in the same basic way as inert fragments. However, the explosive incendiary projectile produces a number of holes in a fuel tank, and the ignition source persists for a relatively long time. Thus, there is a better chance of the ignition source and fuel supply coinciding. These explosive projectiles can also start fires even when the point of impact is outside the fuel tank presented area, thus increasing the overall chance of fire.

The vulnerability of the fuel system to external blast is often disregarded in analyses, as being a negligible contributor to the vulnerable area of the entire aircraft. It is, however, of interest that the critical distance for the direct ignition of free gasoline (i.e., in open containers) by explosive detonation is approximately 25 times the diameter of a spherical TNT charge (Ref. 15).

A shaped charge of sufficient size may so disrupt the fuel tank and its surrounding structure that the incident of a fire becomes of secondary importance.

8–12. (C) POWER-PLANT DAMAGE

Test results show that the effect of HE shell casing fargments is important in hits on engines, due to the presence of fuel lines, relatively fragile accessories, wiring, etc. Such tests also indicate that engines are vulnerable to near impacts of the 20-mm shell, due in large part to the fragmentation effect. Because fragmentation effects are of such significance, test data obtained with only bare charges are not always applicable.

Unlike airframe damage, which is increased by the delayed functioning of an HE shell, engine damage is not as critically dependent on the fuzing type and performance.

It is noteworthy that the location and manner of installation of an engine may be a more important factor than is the type of engine in determining the engine's vulnerability in a particular situation. Thus, any comparisons of the relative vulnerabilities of different engine types must be on the basis of everything else being equal. It is in this light that the following comparisons should be considered The radial, aircooled, reciprocating engine is the most damage resistant of the aircraft power plants; the inline, liquid-cooled, reciprocating type is significantly more vulnerable, due primarily to the effects of loss of the coolant of the gas turbine engines, the axial-flow type tends to be more vulnerable than the centrifugal-flow type, due to its larger and more vulnerable compressor.

"A" damage to an air-cooled piston engine is usually confined to the fuel systems. Oil damage ordinarily causes the engine to stop in 10 to 15 miuntes, giving a "B" kill. Similarly, a bullet hole in the coolant system of a liquid-cooled piston engine will usually cause the engine to stop in about 10 minutes, giving a "B" kill.

The gas turbine engine (on a functional basis) can be divided into six sections, as shown in Fig. 8–5. A kill of any one of these six sections is considered as a kill of the engine. A necessary but not a sufficient condition for the kill of any section is the perforation of the casing or exterior skin (except, of course, for trajectories into the air intake).

In a vulnerability analysis, the probability of a kill, given a hit, is estimated for each section. To illustrate the method, the following description, based on the J–47 engine, is cited from Ref. 19.

"In the accessory section, the vulnerable parts consist of the fuel pumps, fuel lines, fuel

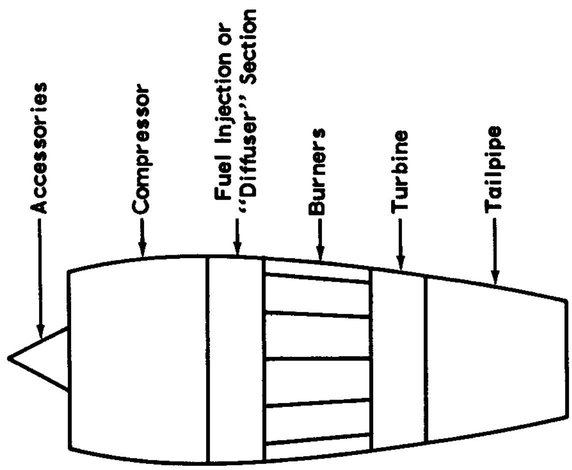


Figure 8–5. Gas Turbine Engine, Functional Diagram

filters, the governor, the oil pump, and the oil lines. The assumption is made that the fragment has to have sufficient striking velocity to perforate 0.25-inch dural in order to damage these parts of the accessory section. Given a perforation, the fuel or oil pressure will be lost and the fuel or oil will leak into the compressor and start a fire. Therefore, the engine will have to be shut off or will stop, owing to the loss of fuel pressure. The engine can continue to operate without oil pressure for about 15 minutes, but it is assumed the engine is shut off in order to minimize the fire hazard.

"The compressor has approximately a 0.5-inch dural casing which must be perforated in order to do serious damage. The last two stages of the compressor are usually not considered vulnerable, on the assumption that the blades that break loose will not adversely affect the engine performance. The front face of the compressor, of course, is not covered by a heavy casing, and the fragment has only to enter the compressor to cause serious damage. Where a fragment does penetrate the forward portion of the casing or enter the front face of the compressor, the probability that the compressor will be damaged enough to stop the engine is estimated as 0.9.

"The parts of the diffuser section that are vulnerable are the fuel manifold and nozzles. A fragment with sufficient velocity to perforate 0.2-inch dural will be able to sever one of the fuel lines or nozzles, causing a serious fire as well as loss of fuel pressure to the nozzles. Since the fuel manifold and nozzles are approximately one-half of the area of the diffuser, the probability of kill, given a . . . (penetration of) the diffuser, is 0.5.

"The burner section is not vulnerable to fragments unless a very large number hit the section and cause a total hole area of over 7 square inches. This assumption is based on experimental data from all the sources listed previously.

"In the turbine section, sufficient damage to stop the engine can be done to the turbine buckets. From the side of the turbine section, the buckets are 30 per cent of the area, while from the front or rear the buckets comprise 65 per cent of the area. In order to damage the side of the turbine, the fragment has to have sufficient velocity to perforate the equivalent of 0.75 inch of dural and from the front or rear quarter 0.25 inch of dural.

"Given a . . . (penetration of) the turbine buckets, it is assumed the probability of kill is 0.8."

A fragment that perforates the compressor or turbine casing and hits a blade will ordinarily possess sufficient energy to destroy all or part of that blade. (For both the compressor and the turbine, the fragment does not require any remaining velocity to damage the blades, since the latter are rotating at high speeds.) The damaged blade(s), and the fragment, then tend to destroy other blades aft of the location of the first damage. However, it is usually assumed that the loss of only the last two stages of an axial compressor will not cause a kill of the engine. The loss of several turbine blades would probably cause an "A" kill of the engine.

Holing of the fuel manifold is ordinarily assumed to cause an engine "A" kill.

The following are typical assumptions regarding the vulnerability of gas turbine engines to oil or fuel system damage: complete loss of fuel pressure causes an "A" kill of the engine; even if the loss of fuel pressure is only partial, there is still a high likelihood of a lethal fire being ignited; and partial or complete loss of oil pressure will cause a "B" kill.

Burners are relatively invulnerable, holes up to 9 square inches having been cut in them with little effect on engine operation.

A fairly common assumption is that a hole of approximately 15 square inches is required for an "A" kill. However, for tail attack aspects, API projectiles have been found to pass through the burner section, causing a kill of the compressor and/or diffuser. It is to be noted that, although the above information refers to a specific axial-flow jet engine, the approach used to determine vulnerability is typical.

There is evidence that gas-turbine engine damage can result in complete engine destruction, due to changes in the thermodynamic cycle; e.g., if the compressor is holed, reducing the flow of cooling air through the engine, the gas temperature at the turbine may rise sufficiently to cause turbine blade failure.

There appears to be some advantage to locating engines in strut-suspended pods, as opposed to encasing them in the wings. With the latter type of configuration, fires caused by engine hits are more likely to cause significant airframe damage.

An engine (piston or gas turbine) may run for a considerable period of time after a fragment or bullet hit before oil leakage causes a kill. Ordinarily, the usual kill categories are used to describe this event, these categories depending primarily on the time variable.

One may also speak of the probability that an engine hit at time zero becomes inoperative at time t. Consider Fig. 8–6 for example. For the hypothetical plot shown, a kill of the engine within less than five minutes is unlikely. Thus, the probability of an "A" kill would be small in this case. By contrast, fragment or bullet damage to a gas turbine engine compressor will cause a kill within a few seconds, or not cause it at all.

In analyzing the vulnerability of an aircraft, it should be realized that, in many cases, the threat of a lethal fire may force shut-down of an engine even if damage is confined to apparently minor systems, such as oil lines in the accessory section. Thus, what is ostensibly category "B" engine damage may cause an "A" kill of the engine.

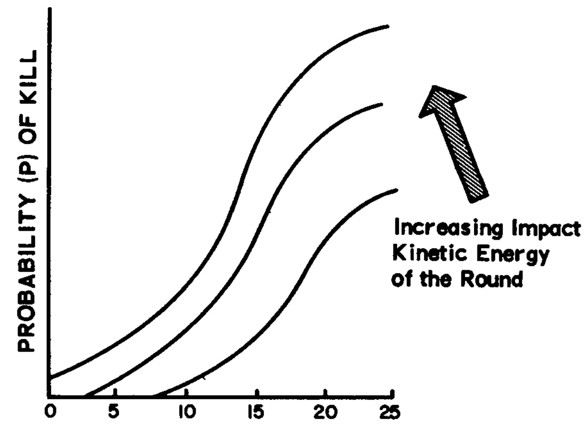


Figure 8–6 (C). Time Effects on Engine Kill by Oil Damage (U)

8–13. (C) PERSONNEL INCAPACITATION OR KILL

The vulnerability of personnel to fragments and bullets has been discussed in Ch. 3, Sec. I, and is covered in more detail in Ch. 5, Sec. II. This information, although directed generally at personnel in the field, will apply in most respects to the aircraft crew. However, further considerations regarding individual position and appropriate stress levels are still in progress.

Data on the vulnerability of personnel in aircraft to high explosive shell are meager. If the assumption is made that the casing fragments add to the pure blast damage, the problem is complicated by the need to consider nonparallel fragment trajectories and secondary fragments created by primary fragment impacts on the airframe or miscellaneous items.

It is ordinarily assumed that any detonation of a projectile with an equivalent weight of at least one-fourth pound of TNT, within a personnel compartment, will kill all crew members in that compartment.

Because in most combat aircraft the personnel are located in a pressurized cabin or compartment, the presented area of the cabin is often taken as the vulnerable area of the personnel. This is usually done for HE shell with an equivalent weight of at least 1/4-lb of TNT, since any hit on the cabin area will result in the fragment spray hitting the personnel.

The vulnerability of personnel at high altitudes is intimately linked with the low ambient pressures and oxygen concentrations encountered. One consequence of these conditions is the need for pressurizing personnel compartments or cabins. Current United States Air Force policy is to provide pressurized cabins for all aircraft with tactical operating altitudes over twenty thousand feet. Unfortunately, combat damage to a pressurized cabin can result in explosive decompression, sometimes with lethal results. This term refers to the rapid expansion of an individual's internal body gases, which occurs when the cabin pressure falls quickly toward the ambient pressure (Ref. 88). An equation for this phenomenon is as follows:

Let RGE = the relative expansion of the internal body gases, then:

$$RGE=\frac{P_c-0.91}{P_a-0.91} \tag{8–1}$$

where

P_c = cabin pressure before damage, in psi,

P_a = final (i.e., ambient) pressure, in psi,

and

0.91 is the vapor pressure of water, in psi, at 98.6° F.

Experiments have shown that the time of decompression is an important factor in the amount of RGE that can be safely tolerated.

Let

t = the time of decompression, in sec.,

and

$RGE_{critical}$ = the maximum RGE that can be safely tolerated for a given value of t,

then

$$RGE_{critical}=2.1+17t \text{ (approximately)}. \tag{8–2}$$

But, approximately,

$$t=0.22\left(\frac{V_c}{A}\right)\sqrt{\frac{P_c-P_a}{P_a}} \tag{8–3}$$

where

V_c = volume of pressurized cabin, in cu. ft.,

A = area of the hole in cabin, in sq. in.,

therefore,

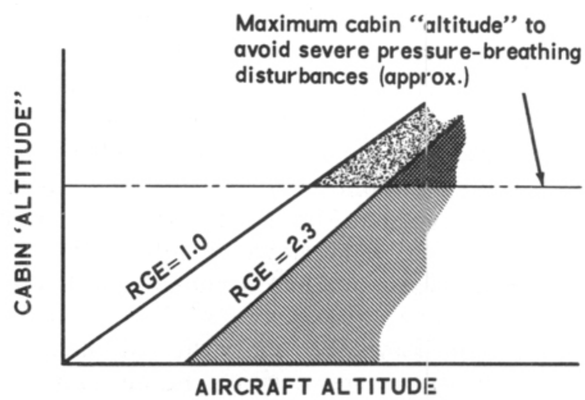
$$RGE_{critical}=2.1+3.8\left(\frac{V_c}{A}\right)\sqrt{\frac{P_c-P_a}{P_a}}. \tag{8–4}$$

This equation is known to give a value that is somewhat low, but is acceptably accurate for most purposes.

For a given cabin volume, hole size, and aircraft altitude, RGE increases faster with increasing cabin pressure than does $RGE_{critical}$. Thus, explosive decompression limits the permissible pressure differential.

The explosive decompression hazard is illustrated by Fig. 8–7 for which $RGE_{critical}$ is assumed to be 2.3.

Tests have been made (Ref. 3) of the damage caused to pressurized cabins by 20-mm HE shell. One such shell, detonated inside a cabin with a volume of 333 cubic feet, caused the pressure differential to drop from 9.5 psi to zero in 7 seconds. Detonation of a 20-mm shell on the cabin skin caused an 18 by 24 inch wound, the pressure differential dropping from 9.5 psi to zero in one-fifth second.



LEGEND

Symbol	Difficulty With Pressure and Breathing?	Risk of Explosive Decompression?
(light stipple)	yes	no
(dark stipple)	yes	yes
(hatched)	no	yes

Figure 8–7 (C). Explosive Decompression Hazard ($RGE_{critical}$ = 2.3) (U)

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In both cases, there was no evidence of internal damage from the blast wave, except immediately adjacent to the point of detonation. Both trials were at sea level ambient pressure.

If we use the second case mentioned to check Eq. 8–3, we obtain

$$t=0.22\left(\frac{333}{18\times 24}\right)\sqrt{\frac{9.5}{14.7}}=0.14 \text{ second.}$$

Note that this is a somewhat smaller value than the actual time of one-fifth second.

The expression for RGE_{critical} tacitly assumes that the crew personnel involved are not protected by pressure suits. Although such equipment can cause discomfort, reduce mobility, etc., they can make explosive decompression situations of considerable severity tolerable to the individual who is properly protected. In one series of tests (Ref. 20), five subjects wearing specially modified Air Force partial-pressure suits were explosively decompressed from the altitude range of 15,000 to 20,000 feet to the altitude range of 50,000 to 60,000 feet. All remained conscious and capable of performing their duties.

Note that, because the physiological damage associated with explosive decompression usually centers in the lungs, the use of a pressure suit alone (i.e., without a properly designed helmet) will generally not provide adequate protection against explosive decompression.

8–14. (C) ARMAMENT DAMAGE

(U) The armament component is specified as consisting of the following classes of items:

1. Bombs, rockets, shells, bullets, or missiles carried by the aircraft.
2. Equipment for sighting, firing, or releasing the aforementioned projectiles.
3. Corollary electronic equipment.

It contributes to aircraft vulnerability in that:

1. Damage may result in a "C" kill of the aircraft.
2. Damage may result in a reduction of defensive ability.
3. Detonation of bombs or warheads by enemy action is possible.

(U) Only fragmentary data are available on the vulnerability of electronic units, gunsights, etc. Essentially all the published data on the vulnerability of the armament component relate to the detonation of cased charges by impacting fragments or bullets. In this regard, it should be noted that of the three classes of items listed above, only the first would ordinarily contribute vulnerability to a quick kill (i.e., KK, K, or A), in that the aircraft is carrying a significant source of energy for its own destruction.

(C) From test firings with fragments, it appears that striking energy is not the determining factor in detonating bare charges. One possible explanation is found in Ref. 21. Assuming that the front layer of the fragment is brought immediately to rest at impact, a plane of arrested motion travels back through the fragment at the speed of sound in steel. For the larger fragments, only a small portion of the fragment can be deformed in the approximately one microsecond available before detonation. Thus, all the energy from a 1/10-ounce fragment may be utilized, but very little of the energy of a rod or large fragment may be made available. The tests cited in Ref. 21 involved the firing of fragments at bare, cast, RDX/TNT (60 per cent/40 per cent). The usual delay observed (between impact and the initiation of detonation) was slightly less than a microsecond.

(C) On the basis of the tests discussed (Ref. 21), is was felt that two possible explanations for the initiation of detonation of a bare or cased charge warranted further investigation: the shock wave spreads into the HE from the point of impact; and impact causes large frictional forces in the adjacent explosive, resulting in "hot spots."

(C) Where the charge is cased, striking energy appears to govern only in certain situations. Further, it is evident from many tests that perforation of the casing is not a necessary condition for detonation of the enclosed explosive. In addition, casing perforation has occurred without any detonation resulting. Thus the casing thickness is not the determining parameter. However, the exposure of the

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